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GENERAL ELECTRIC
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AN OUTLINE OF VACUUM TECHNOLOGY

by

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Minimizing Contamination for Vacuum



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Massachusetts Institute of Technology

Techniques that avoid the pitfalls of contamination in cleanly handling vacuum devices—from electron tubes to walk-in chambers—result in uniformly better operation and in pinpointing trouble spots.

Importance of cleanliness in fabricating, handling, and assembling components of a vacuum system cannot be overstressed. The goals that are to be sought transcend mere surface purity and sterility.

Here on the surface of the earth, nature abhors clean materials; all substances in their customary state have been to some extent contaminated by the very air we breathe, oils and greases, the sweat of our hands, all kinds of smoke (including that from tobacco), lint, dust, soot, detergents, paints, rust inhibitors, dandruff, cosmetics, and many other

ordinary things that pervade the environment. Moreover, many constructional substances adsorb and/or adsorb gases which may give rise to a chemical effect, a common example being the surface oxidation of steels, stainless steels, and aluminum.

At first glance, one would think that the **attainment** of true cleanliness (i.e. elimination of all contaminants: solid, liquid, and vapor) would be practically impossible, and the **maintenance** of such a state even more so. Such a state of affairs is rather close to the truth. All we can hope to do is to reduce the amount of contamination to a total small enough that it does not behave as though our vacuum vessels were leaky. What this means for most practical purposes is that when substances and surfaces inside a vacuum chamber give off gases and vapors, the effect is the same as though there were one or more leaks from the atmosphere.

While some precautions can be taken in the fabrication of components, there are many more pitfalls between fabrication and final assembly. Knowing what these dangers are is more than half the battle; a considerable part of the rest can be skirted by giving the operators a training program

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during which it is aimed at making the avoidance of contaminants in the design, construction, and handling of vacuum components become a part of common sense—or even better—of habit.

Within limits it is true that surface contamination can be removed by chemical or mechanical means. Nevertheless, the application, or rather misapplication, of degreasing and other chemicals, abrasives, tools—to relatively clean surfaces, almost always leaves something in place of what it took away. Therefore, common sense tells us that, if possible, deliberate contamination of a clean surface by immersion in less-than-clean solvents or chemicals, should be avoided. It is also possible that reactive chemicals (pickles and the like) can leave contaminant gases on the surface of metals.

There are methods for reducing contamination after assembly; also during or after pumping. Such procedures include baking, radio-frequency (induction) heating, electron bombardment, sometimes ion bombardment, and heating by simple passage of current (such as the conduction heating of filaments). These techniques are used separately or in combination.

Refrigerant and/or chemical trapping is used with the excitation techniques mentioned, which hopefully convert the contamination to vapor, in order to hold these vapors by condensation or combination in places where they will not be re-released onto clean surfaces from which they have just been removed. It goes without saying that all such methods are rendered much more difficult if the surfaces are not as clean as possible before assembly. We cannot expect these methods to remove the effects of oil, grease, paint, or chemicals. Finger-prints

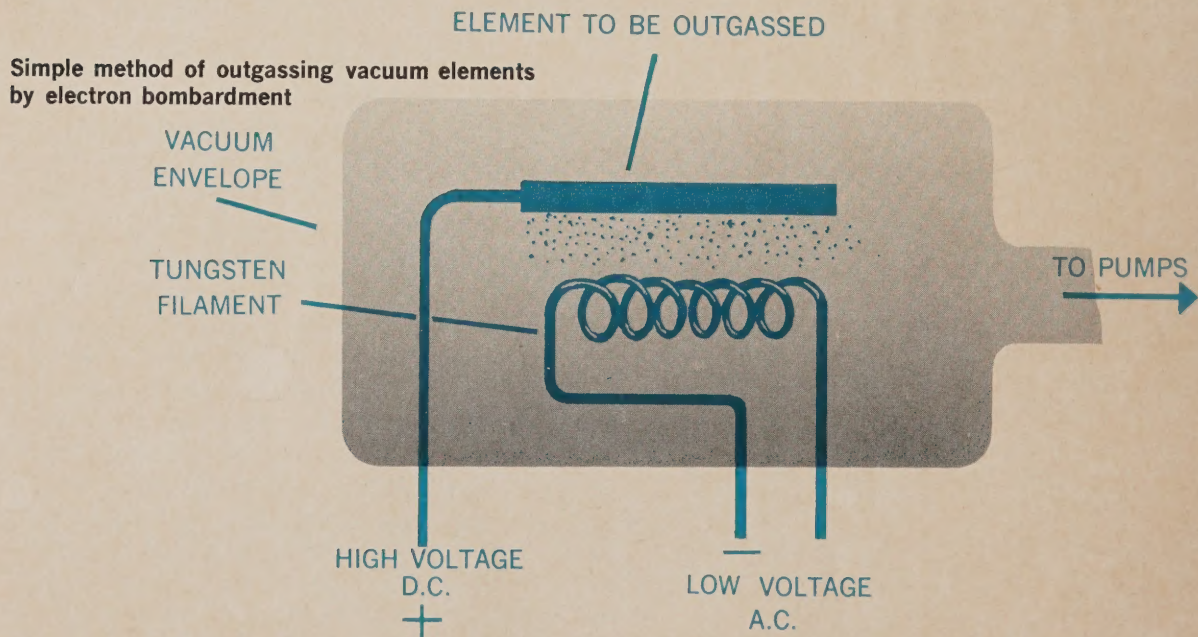
leave fatty acids and mineral salts that can cause corrosion.

Although baking at 450 C or higher for long periods removes most of the adsorbed water and water vapor, and possibly some of the absorbed gases and other contaminants, this type of treatment cannot be used in systems incorporating rubber O-rings or seals, plastic insulation, and any other materials with low decomposition temperatures or high vapor pressures.

Metal vessels can, in some cases, be heated by r.f. induction, although this is not a usual practice. Induction heating is more commonly used for outgassing metal parts inside a glass or other non-conducting vacuum envelope; this must, of course, be done judiciously with due regard for O-ring seals, and for the distorting, stressing effects of non-uniform thermal expansion.

Electron bombardment can be used for local heating of certain elements in vacuum devices where there is a source of electrons, or a cathode, that can be focused or directed toward the component to be outgassed. A simple tungsten filament can thus be used to outgas metal structures (anodes, grids, etc.) that are continuous to it, see below.

In using electron bombardment, some caution must be exercised to avoid overheating since it is very easy to melt even refractory metals. If the anodic structures are contaminated, overheating can also cause evolution of enough gas to produce ionization in the vessel. This may be useful in some cases, harmful in others. For example, oxide-coated cathodes should be shielded from positive-ion bombardment, and from any material emitted by either sputtering or evaporation from neighbor-



ing structures. Activated (converted) oxide-coated cathodes are very easily poisoned by a number of elements and compounds, including water-vapor, which changes the oxide coating to an irreversible hydroxide having no emissive power.

Heating of components in vacuum devices works both ways. When a filament or cathode is heated, some of the gases and volatile constituents impinge upon other components nearby. Condensation, adsorption, and absorption can then take place on the cooler surfaces, and may cause trouble if in turn they are heated at a later time.

Some contamination might take place after assembly, and during pumping. Backstreaming or migration of oil molecules from diffusion pumps onto clean metal surfaces within the vacuum chamber is one type of such contamination. Modern pumping systems partially eliminate this source by proper design, use of low vapor-pressure fluids in pumps, use of compound cold traps and baffles, and by substitution of various types of getter-ion, appendage, or sublimation pumps for oil-diffusion pumps.

Some contamination of metal parts arises from particular methods fabrication. For example, in making experimental or prototype devices, some of the components might be sheet-metal spinnings, as this is a convenient way to make one or a few formed parts without expensive dies. In spinning sheet metal there is always a danger that certain contaminants such as soaps, proprietary lubricants, dirt, dust, oil, or grease, may become embedded in the metal, and overlaid by the spinning tool. The tool itself, if made of a bronze alloy containing lead, zinc, or other volatile constituent, could be a source of contamination. These remarks apply also to polishing. Electropolishing is safer than mechanical buffing, except for high-voltage electrodes, which should be polished only with pure, levigated alumina on new or clean cotton wheels.

In using solvents for degreasing (trichlorethylene, perchlorethylene, acetone, Freons, alcohols, etc.) a rule that must be strictly observed is that all *final* rinses be in *fresh, virgin* solvent. Solvents, of course, should be chosen for high purity (use reagent grade only, for rinsing) and freedom from residues. A solvent used for removing fingerprints, for example, is contaminated with fatty acids that subsequently will deposit on anything dipped into that solvent.

The variety of reactive chemical treatments for metals, including electropolishing and electroplating, is too extensive to present here. All such treatments, however, should be followed by very thorough rinsing, first in running tap water (if your tap water is potable, not too hard, or not too heavily chlorinated), and then in several changes of dis-

tilled or preferably deionized water. In some cases the final rinse water should be at boiling temperature. This should be followed by rinsing in two or three changes of absolute, reagent-grade methanol or acetone, and then drying in an air oven at 80 C. Metal pieces that are to be plated after cleaning should not be dried but transferred immediately to the plating or strike bath after the water rinses.

Plating, electropolishing, and reactive chemical cleaning solutions should be made up fresh at the first sign of precipitation, clouding, or smut. Plating baths should be filtered either continuously or frequently, and they should be kept covered to prevent dust contamination. In most cases plating anodes should be enclosed in special textile bags to prevent impurities or inclusions from contaminating the solution.

All plants and laboratories engaged in fabricating vacuum and electron devices should have access to facilities for hydrogen and vacuum firing. It has been fairly well established that stainless steel, heat treated at 1000 C in dry hydrogen of dewpoint minus 50 C or lower retains little but occluded or adsorbed hydrogen. For many purposes, it is merely necessary to bake out at 450 C during evacuation to eliminate the hydrogen. Often this firing operation can be combined with a brazing procedure, since austenitic stainless steels cannot be satisfactorily brazed for vacuum purposes at temperatures much below 1000 C (the reduction temperature of the chromium oxide on the surface which prevents wetting) in hydrogen of dewpoint higher than -40 C. Other metals, such as nickel, OFHC* copper, Kovar,[®] molybdenum and tungsten, can be fired in ordinary commercial hydrogen in ceramic muffle furnaces. Steels, invar, mumetal, Armco iron, Hypernik, Co-netic (and some other magnetic alloys), Inconels[®] and Nichrome,[®] various glass-sealing alloys, must be fired in dry hydrogen as with stainless steel, if they contain appreciable amounts of chromium or high percentages of iron.¹ Since most atmosphere furnaces use city-gas pilots and/or flame curtains, some precautions must be taken when the work is removed from the furnace to keep it away from the gas flames. One way to do this is to use covered boxes or boats. I have seen atmosphere furnaces used with city-gas pilots burned with insufficient air, causing a gentle rain of oily soot to fall from the ceiling. And this was being

*Oxygen-free, high-conductivity.

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"Inconel" is registered trade mark of International Nickel Company; "Nichrome" of Driver-Harris Company.

¹Make sure that no work placed in hydrogen or vacuum furnaces where critical vacuum components are to be fired, are plated with cadmium, zinc, lead, or other volatile material, which will contaminate the furnace by depositing on the walls and on subsequent work.



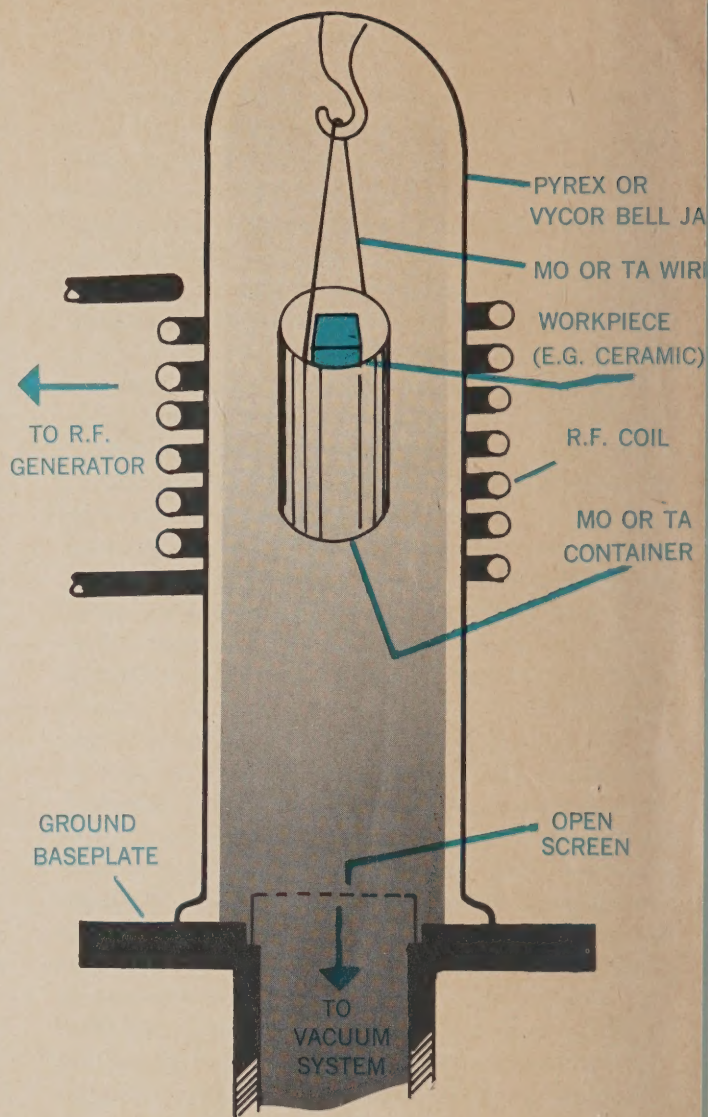
done in the same room where tubes were being assembled!

Sometimes it is necessary or desirable to vacuum fire certain metals. There is no particular advantage in vacuum firing stainless steel, since it is likely to pick up atmospheric gases immediately upon removal from the vacuum chamber. Vacuum firing is conveniently done in furnaces especially designed for this purpose. On a laboratory scale, if a clean, fast vacuum system is available, the work can be suspended in a glass or Vycor® belljar (or contained in a molybdenum or tantalum can or bucket, suspended axially in the belljar) which is seated on a metal baseplate. The work is heated by surrounding the jar with a water-cooled copper coil connected to an r.f. induction generator. Vacuum firing is mandatory for tantalum, titanium, columbium, zirconium, and other metals which react with hydrogen to form hydrides.

The cleaning of ceramics presents a special problem; special, that is, for each kind of ceramic. This is of interest in thin-film deposition, where cleanliness of the substrate must be as near absolute as possible. Reactive chemical treatments are to be strictly avoided for any material not having a glazed or glassy surface, since it is practically impossible to rinse the reaction products and chemicals out of the relatively rough surfaces of most ceramics. Clean, pure, volatile solvents can be used for degreasing, but, in general, water should not be used for such materials.

Thorough drying in an air oven at 80 C is to be followed, in the case of alumina, by either hydrogen or vacuum firing at 800 C. A slight darkening or discoloration may occur in either case. This is caused by reduction to metal, for example, aluminum oxide to aluminum or it may be caused by deposition of metal from the boat or bucket. In either event the amount is negligibly small, and is a small price to pay for the amount of out-gassing obtained by the firing.

Some ceramics, however, are seriously reduced to semimetallic materials in either hydrogen or vacuum. The manufacturer should be consulted when ceramics other than those mentioned here are to be used, or a test piece should be fired. Alumina, quartz, and sapphire can be either hydrogen or vacuum fired if sudden heat shocks are avoided. Boron nitride, which is easily machined, finds wide use in vacuum designs, and does not require the firing operation that is necessary for most other ceramic materials to convert them from a green state (containing water of crystallization) to a



Induction heating for outgassing

dense, impervious state. Since all machining operations on boron nitride can be performed dry, if clean tools are used and proper precautions taken in handling (avoidance of skin contact, etc.) the piece can be vacuum fired in a well-outgassed molybdenum boat at 800 C. A slight discoloration sometimes occurs, but this does no harm. Hydrogen firing has also been used successfully with boron nitride.

Neoprene O-rings are not used in ultra-high vacuum devices, but do find much use in less stringent equipment. New O-rings should always be used in cleaned components, and they should be handled by a clean technique; no further cleaning should be required, and the use of solvents such as acetone, alcohol, trichlorethylene, etc., should be avoided, since it has been found that these tend to swell the material and to allow the evolution of gases, mostly butane.

If cleaning is required, a small amount of de-

"Vycor" is the registered trade mark of Corning Glass Works for a 96% silica glass.

tergent in cool water may be used, followed by thorough rinsing in deionized water, and baking at not more than 100 C in an air oven for several hours. If grease is required, Apiezon "N"[®] should be used and applied very sparingly. Gloves should be used by workers to avoid skin contamination. The greasing is done just prior to assembly.

O-rings of Viton[®] elastomer are now in common use, and are replacing Neoprene in many vacuum applications. This is a fluorelastomer which has significantly lower vapor pressure and may be used at higher temperatures than Neoprene. Viton O-rings are readily available in the standard O-ring sizes. The same rules for cleaning and handling Neoprene also apply to Viton, or to any other elastomer that is to be used.

All components that have been cleaned and/or fired must be stored in airtight containers. For most practical purposes, three or four layers of ordinary, new polyethylene bags, or "Saran-Wrap" is suitable. Hot parts should not be wrapped in plastic. Vacuum-fired parts should be allowed to cool to room temperature in the belljar before admitting air. Two layers of fresh aluminum foil which have been rinsed in clean acetone may also be used for wrapping. Ideally, the storage of clean parts should be in vacuum. Certain metal components can be sealed in evacuated glass tubes.

Assembly operations under clean conditions have been very widely investigated and reported, not only in the manufacture of vacuum devices, transistors, etc., but also in activities such as electrical measuring instruments, precision ball-bearings, watches and clocks, and automotive instruments. Under the best circumstances the following conditions must be met.

1. Rooms should be sealed and efficiently air-conditioned. There should be a slight positive pressure within so that outside dust is less likely to enter. Laminar-flow modules, dust filters, and electrostatic precipitators are useful, and must be periodically checked, cleaned, or changed. The relative humidity must be no higher than 40-50 per cent. Values much lower than this become uncomfortable for personnel. Furniture (benches, stools, cabinets) should be of metal, glass, or plastic. Walls, floors, and ceilings should be of materials that do not flake or shed. Plaster, concrete, brick, cinderblock, and wood must be well covered with several coats of gloss or semigloss washable plastic paint. Enameled metal wall panels with gasketed or covered seams make an excellent interior. Unless

the building is equipped with remote vacuum-cleaner lines, periodic cleaning should be done with clean, damp cloths. Ordinary portable vacuum cleaners blow fine dust particles and should not be used.

2. Personnel *must* wear approved protective clothing, cap-a-pie, for example, monofilament nylon, orlon, dacron, or the like; caps, gloves, coats, or wraparounds, and sometimes face-masks should be worn. Nylon monofilament gloves (full-fashioned for better fit) with plastic-coated palms, are available. These should be discarded at the first sign of wear, cracking, or fraying. Polyethylene or vinyl foot coverings should be worn. All garments and boots should be donned, taken off, and stored in an anteroom. The garments should be closely inspected and washed at regular intervals. Washing, of course, should be followed by copious rinsing in clean water to remove all traces of soap or detergents that might leave residues. Personnel must be indoctrinated to wear these garments at all times while inside the area. Gowns and coats must completely cover ordinary clothes, and caps must entirely cover hair of both men and women. Women should not use face powder; special cosmetics are available. Visitors should be discouraged, but, when necessary, they should be subject to the same precautions, and extra garments and boots should be ready in the anteroom.

3. In some cases, additional precautions may be taken, namely, the use of bench glove-boxes, which can be supplied with special ultra-clean, dry, and protective atmospheres. These boxes can be equipped with low-power binocular microscopes for working on small components. It is sometimes required that parts always be handled with clean instruments and tools, which are kept inside the glove-box.

4. Work should be carried to and from this area in sealed or evacuated containers, and through especially designed double ports that prevent the entry of contaminated air from outside.

Ordinary rubber finger-cots should not be used, as the rubber contains volatile materials. Operators should be cautioned against touching their faces with gloved hands, for obvious reasons. Hot coffee and all other food must be prohibited in the critical areas, and smoking should be grounds for dismissal.

These conditions are, of course, extremely rigorous, and modifications may be made to fit less stringent requirements.

The point is that if as many sources of contamination as possible are eliminated, by whatever means necessary, results are more likely to be uniformly good; and if trouble develops, the source of it is more likely to be apparent.

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"Viton" is the registered trade mark of the E. I. du Pont de Nemours Company.

Suggestions for Vacuum Measurement

By WILLIAM G. LONG/Senior Research Engineer
Atomics International

With reference to the article, "How Shall We Measure Vacuum?" in the September issue of R/D, I was a little surprised that only 41 per cent of the responses indicated favoring the present system. It does not seem likely that a new system of units will remove the inadequacies of the current method of reporting pressure. Surely any new system adopted now would only confuse the situation. I believe that we should be more concerned with a proper definition of the vacuum environment than with the label attached to the units of pressure.

Let me suggest how we might amplify pressure definition. Instead of reporting a test at 1×10^{-8} torr, a graph of pressure as a function of time would be included in each report or paper. This shows immediately that the test began at 8×10^{-6} torr, the pressure slowly decreased through the 10^{-7} torr range, and reached an ultimate pressure of 1×10^{-8} torr. This graph would eliminate Mr. Male's "cheater" who "glibly speaks of being in the 10^{-8} range."

Included is a graph, Fig. 1, which shows a typical pressure trace for one of our systems with the specimen temperature at 1000 F. The high initial gas loads at temperature raise the system pressure into the high 10^{-6} torr range, and an ultimate pressure of 1×10^{-8} is obtained after approximately 800 hours. The only adequate method of describing test pressure, therefore, is to present a pressure-time curve. We do not, however, attach any particular significance to a test which was conducted at 2×10^{-8} compared to one at 8×10^{-8} torr, other than the fact that the former environment is "cleaner." The degree of absolute difference depends upon the accuracy associated with measuring devices.

I was particularly impressed by Dr. Chuan's description of the basic motivation for creating a vacuum condition. That is, "to minimize contamination of a mechanism of interest by unwanted molecules." The question arises as to how contamination is presently defined. We do not ordinarily specify the makeup of the 10^{-8} torr pressure.

Dr. David Lichtman presented the case for determination of partial pressures using the mass

spectrometer in the February 1964 issue of R/D. It would seem to be a valuable contribution to vacuum technology to define the constituents of the environment of each test of any duration. For instance, is the "contamination" the same in an oil-diffusion pumped chamber at 10^{-7} torr as in a system at the same pressure maintained by an ionization pump? Probably not. How can we really interrelate cause and effect in vacuum work until the contamination is identified?

We have done extensive research* at Atomics International on the effects of contamination on materials and components under vacuum at high temperature. We know that very minor amounts of certain contaminants can adversely affect component performance. I would like to see contamination defined in partial pressures of constituents. If this practice were adopted, it might be easier to correlate material data from different testing laboratories. I believe that a report accompanied by a pressure-time curve and a table of gas constituents would improve the quality of vacuum test reporting.

* Work performed under AT(11-1) GEN-8

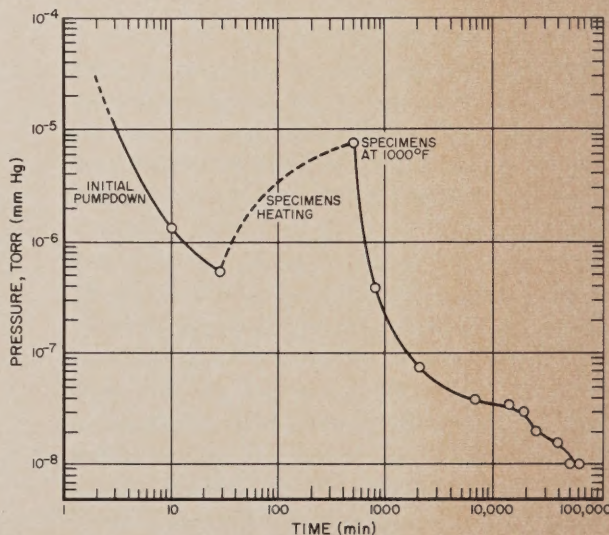


Fig. 1, Above. Graph illustrating difficulty of defining test pressure. Ultimate pressure of 1×10^{-8} torr was obtained after 800 hours at temperature.

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ABSTRACT

This report comprises a portion of the lecture material developed for a course in high vacuum technology, which was presented at the Research Laboratory (February to May 1963 and September to December 1963).

The main divisions are:

- I. Introduction
- II. History of Vacuum Technology
- III. Primary Quantities, Units, and Constants
- IV. Empirical Relations and the Kinetic Theory of Gases
- V. The Transport of Gas in Vacuum Systems
- VI. Pumping
- VII. Gauges
- VIII. Vacuum Seals
- IX. Valves
- X. Materials of Construction
- XI. System Design
- XII. Leak Detection
- XIII. Deposition of Films
- XIV. Manipulation of Volatile Compounds
- XV. Miscellaneous Industrial Applications
- XVI. Surface Chemistry and Physics
- XVII. Manufacturers of Vacuum Equipment and Special Materials

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AN OUTLINE OF VACUUM TECHNOLOGY*

Richard W. Roberts

I. INTRODUCTION

During the next twelve sessions we shall consider the general techniques and principles involved in producing, measuring, and using a vacuum. By vacuum, I mean any pressure less than atmospheric pressure, and we shall consider the range one atmosphere to 10^{-15} atmosphere.

A. OUTLINE

A tentative outline of the contents of the twelve sessions is as follows:

1. Introduction to course, seventeenth century pneumatics, kinetic theory of gases
2. Vacuum system considerations, basic vacuum calculations
3. Vacuum pumps - 1
4. Vacuum pumps - 2
5. Vacuum gauges - 1
6. Vacuum gauges - 2
7. Vacuum accessories - 1
8. Vacuum accessories - 2
9. Materials of construction - 1
10. Materials of construction - 2
11. System design and leak detection
12. Applications to problems in physics, chemistry, and technology.

B. LITERATURE-GENERAL VACUUM REFERENCES†

Outside preparation will consist primarily of reading. The books Principles of Vacuum Engineering (Chapman and Hall, London, 1961) by M. Pirani and J. Yarwood and Ultrahigh Vacuum and Its Applications (Prentice-Hall, New Jersey, 1963) by R.W. Roberts and T.A. Vanderslice will serve as texts.

*The original report was printed under the title "A Course in High Vacuum Technology."

†See also Appendix B.

The following is a list of more important references for the student who desires more information in a specific area.

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II. HISTORY OF VACUUM TECHNOLOGY

A. PRE-SEVENTEENTH CENTURY

It was observed that it was necessary to have a hole in the top of a barrel in order to drain wine out of the bottom. The explanation for this phenomenon was that "nature abhors a vacuum" and dates back to Aristotle.

B. SEVENTEENTH-CENTURY PNEUMATICS

1. Galileo

Galileo Galilei (1564-1642) mentioned in his Dialogues Concerning Two New Sciences (1638) that a suction pump would not raise water more than about 34 feet, but could offer no satisfactory interpretation for this limitation.

2. Torricelli

Evangelista Torricelli (1608-1649) a student of Galileo, postulated the existence of an atmospheric pressure and that it was this pressure which determined the height to which a liquid could be made to rise by suction. He invented the mercury barometer (ca 1640).

3. Pascal

Blaise Pascal (1623-1662) suggested (1647) that the pressure exerted by the atmosphere may vary with altitude. His brother-in-law, Perier, carried a mercury barometer to the top of the mountain Puy-de-Dome in 1648 and observed that the height of the mercury column decreased as the altitude increased.

4. von Guericke

Otto von Guericke (1602-1686), the mayor of Magdeburg, is generally credited with inventing the vacuum pump. Using this pump he exhausted the air from a sphere composed of 2 hemispheres. Two teams of eight horses pulling in opposite directions were unable to overcome the atmospheric pressure holding the halves together. As soon as air was admitted, the halves fell apart.

5. Boyle

Robert Boyle (1627-1691) combined the vacuum pump and the mercury barometer and repeated the "Puy-de-Dome experiments" in the laboratory. He made many experimental advances and detailed studies of the properties of gases.

In 1669, Boyle and Denis Papin devised a pump which would reduce the pressure in vessel to less than one-hundredth of an atmosphere.

C. TWENTIETH-CENTURY ADVANCES

These will be discussed during the balance of the course.

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III. PRIMARY QUANTITIES, UNITS, AND CONSTANTS

"I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of Science, whatever the matter may be." --Lord Kelvin (1824-1907).

A. FUNDAMENTAL QUANTITIES

Fundamental quantities include length (l), mass (m), time (t), charge (q), and temperature (T). All of the other quantities used in physics and chemistry can be expressed in terms of these. These quantities are usually given in one of the following three systems of units: English gravitational, meter-kilogram-second (mks), and centimeter-gram-second (cgs).

B. DERIVED QUANTITIES

Some derived quantities are defined in Table I, together with their units in the cgs and mks systems. A body is said to possess energy if it can do work. Potential energy, V^1 , is the energy a body has by virtue of its position, and kinetic energy, T , is the energy it has due to motion; $T = 1/2 mv^2$. Energy may be expressed in various units; Table II relates them.

Pressure is a term frequently used in vacuum technology. As we have seen in Table I, it is defined as the force exerted over an area. Table III lists conversion factors for different pressure units. Another unit of pressure is the bar, one microbar = 10^{-6} bar = 1 dyne per cm^2 . In most vacuum work, pressure is usually expressed in units of torr in honor of Torricelli who invented the barometer. One torr is the pressure exerted by a column of mercury 1 millimeter high at 0°C and 45° latitude at sea level.

C. PHYSICAL CONSTANTS

A list of physical constants is given in Table IV.

D. LARGE AND SMALL NUMBERS

Very large and very small numbers may be conveniently expressed as powers of 10. For example:

$$1,000,000,000 = 1 \times 10^9, \text{ and}$$

$$0.000000067 = 6.7 \times 10^{-8} \quad .$$

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TABLE I

Definitions and Units for Derived Quantities

<u>Derived Quantity</u>	<u>Symbol</u>	<u>Definition</u>	<u>Unit (cgs system)</u>	<u>Unit (mks system)</u>
speed	v	$v = \frac{dl}{dt}$	cm/sec	m/sec
acceleration	a	$a = \frac{dv}{dt} = \frac{d^2l}{dt^2}$	cm/sec ²	m/sec ²
momentum	p	$p = mv$	g cm/sec	kg-m/sec
force	F	$F = \frac{dp}{dt} = ma$	dyne	newton
pressure	P	$P = \frac{dF}{dA}$	dyne/cm ²	newton/m ²
work	W	$W = \int \underline{F} \cdot d\underline{l}$	erg	joule

where: l = length
t = time
m = mass
cm = centimeter
m = meter
g = gram
kg = kilogram
s = second
A = area

TABLE II

Factors for Conversion of Energy Units
(from Perkins' Introduction to General Thermodynamics,
John Wiley and Sons, publishers)

	Gram- calories (4°C)	Joules	Foot- pounds	Kilog.- meters	Liter-atm	Horse-power hours
Gram-calorie	1.	4.185	3.087	0.4267	4.130×10^{-2}	1.559×10^{-6}
Joule	0.2389	1.	0.73756	.1019	9.869×10^{-3}	3.725×10^{-7}
Foot-pound	.3240	1.356	1.	.13826	1.3381×10^{-2}	5.0505×10^{-7}
Kilog.-meter	2.343	9.806	7.2327	1.	9.678×10^{-2}	3.6529×10^{-6}
Liter-atm	24.21	101.32	74.733	10.333	1.	3.7734×10^{-5}

TABLE III

Conversion of Pressure Units
(from Perkins' Introduction to General Thermodynamics,
John Wiley and Sons, publishers)

	Dynes per sq cm	Grams per sq cm	Torr (mm of mercury)	Atmospheres	Lb per sq in
Dynes per sq centimeter	1.	1.0198×10^{-3}	7.5010×10^{-4}	9.8697×10^{-7}	1.4504×10^{-5}
Gram per sq centimeter	980.6	1	7.3551×10^{-1}	9.6777×10^{-4}	1.4223×10^{-2}
Kilogram per sq meter	98.06	10^{-1}	7.3551×10^{-2}	9.6777×10^{-5}	1.4223×10^{-3}
Torr (millimeter of mercury)	1332.	1.3595	1	1.3158×10^{-3}	1.9337×10^{-2}
Atmosphere	1013200.	1033.3	760	1	14.696
Pound per sq inch	68944.	70.308	51.715	6.8046×10^{-2}	1
Pound per sq foot	478.78	4.883×10^{-1}	3.5912×10^{-1}	4.7252×10^{-4}	6.9445×10^{-3}

TABLE IV

Physical Constants

Avogadro's number	N'	$6.0226 \times 10^{23} \text{ mole}^{-1}$
Faraday constant	F	$9.6491 \times 10^4 \text{ coulomb mole}^{-1}$
Electronic charge	e	$1.6021 \times 10^{-19} \text{ coulomb}$
Boltzmann constant	k	$1.3805 \times 10^{-16} \text{ erg } ^\circ\text{K}^{-1}$
Gas constant (see Table V)	R	$8.31432 \text{ joule } ^\circ\text{K}^{-1}$
Planck constant	h	$6.6252 \times 10^{-27} \text{ erg}$
Speed of light	c	$2.997930 \times 10^{10} \text{ cm sec}^{-1}$
Electron rest mass	m_e	$9.1090 \times 10^{-28} \text{ g}$
Proton rest mass	m_p	$1.67239 \times 10^{-24} \text{ g}$
Neutron rest mass	m_n	$1.67470 \times 10^{-24} \text{ g}$

NOTE: For a more complete listing of physical constants see E.R. Cohen, J.W.M. Dumond, T.W. Layton, and J.S. Rollett "Analysis of Variance of the 1952 Data on the Atomic Constants and a New Adjustment, 1955," Rev. Mod. Phys., 27, 363 (1955).

IV. EMPIRICAL RELATIONS AND THE KINETIC THEORY OF GASES

A. EMPIRICAL RELATIONS

A variety of empirical relations regarding the properties of gases have been discovered since the time of Boyle. In general, each relation is known by the name of the discoverer.

1. Boyle's Law

Boyle's Law (1662): at constant temperature, the volume, V , of a gas varies inversely as the pressure. That is

$$PV = \text{Constant (for } T \text{ fixed).}$$

2. Charles' Law or the Law of Gay-Lussac

Charles' Law (1787) or the Law of Gay-Lussac (1802): at constant pressure, the volume of a gas varies linearly with temperature, i. e.,

$$V_T = V_{0^\circ\text{C}} (1 + \alpha T),$$

where $V_{0^\circ\text{C}}$ is the volume at 0°C , and α is the coefficient of thermal expansion. Regnault (1847) showed that $\alpha = 1/273$, and more recently $\alpha = 1/273.15$.

3. Avogadro's Law

Avogadro's Law (1811): equal volumes of gas at the same pressure and temperature contain an equal number of molecules. One mole of gas at STP (i. e., standard temperature and pressure, $T = 273^\circ\text{K}$, $P = 1 \text{ atm}$) occupies 22.4 liters.

4. Ideal Gas Law

Ideal Gas Law:

$$PV = NRT, \text{ or}$$

$$PV = nkT,$$

where R is the molar gas constant, k is the Boltzmann constant, N is the number of moles of gas, n is the number of molecules, and T is the temperature in

$^{\circ}\text{K} (^{\circ}\text{K} = ^{\circ}\text{C} + 273.15^{\circ})$. Values for the molar gas constant, R , for various units of pressure and volume are listed in Table V.

5. van der Waals' Equation

$$\left(P + \frac{a}{V^2} \right) (V - b) = NRT,$$

where a and b vary with the gas.

6. Dalton's Law of Partial Pressures

Dalton's Law of Partial Pressures (1801): the total pressure of a mixture of gases is equal to the sum of the partial pressures of the component gases, i.e.,

$$P = \sum_i P_i \quad .$$

7. Graham's Law of Diffusion

Graham's Law of Diffusion (1829): the rate of diffusion of gas, v , is inversely in proportion to the square root of its density, or its molecular weight, i.e.,

$$\frac{v_{\text{O}_2}}{v_{\text{H}_2}} = \sqrt{\frac{M_{\text{H}_2}}{M_{\text{O}_2}}} \quad .$$

B. KINETIC THEORY OF GASES

All of these empirical relations among the macroscopic variables can be derived theoretically from the kinetic theory of gases.

1. Assumptions

The kinetic theory of gases assumes that a gas consists of atoms and molecules, that collisions between these molecules and with the walls of the container can be treated with the conservation laws of classical mechanics, and that statistical methods may be employed.

2. Pressure

The pressure a gas exerts on the walls of a vessel is due to the impact of molecules with the walls.

3. Velocity Distribution

Molecules in a gas travel with different velocities. The distribution of velocities has been calculated theoretically (Maxwell-Boltzmann) and has been shown experimentally to be given by the expression

$$f(v) = \frac{4}{\sqrt{\pi}} \left(\frac{m}{2kT} \right)^{3/2} v^2 e^{-\frac{mv^2}{2kT}}.$$

It can be shown that

(a) The most probable velocity, v_p is given by

$$v_p = \sqrt{\frac{2kT}{m}} = \sqrt{\frac{2RT}{M}} = 12,895 \sqrt{\frac{T}{M}} \text{ cm sec}^{-1}$$

(b) The average or mean velocity, $\bar{v}$, is given by

$$\bar{v} = \sqrt{\frac{8kT}{\pi m}} = \sqrt{\frac{8RT}{\pi M}} = 14,551 \sqrt{\frac{T}{M}} \text{ cm sec}^{-1}$$

(c) The root mean square velocity, v_{rms} , is given by

$$v_{rms} = \sqrt{\frac{3kT}{m}} = \sqrt{\frac{3RT}{M}} = 15,794 \sqrt{\frac{T}{M}} \text{ cm sec}^{-1}$$

For example, the average speed of a hydrogen molecule at 0°C is $169,200 \text{ cm sec}^{-1}$ and that of a mercury atom at 0°C is $17,000 \text{ cm sec}^{-1}$. At 27°C the average speed of a hydrogen molecule increases to $1.768 \times 10^5 \text{ cm sec}^{-1}$ or 3960 miles per hour (about the speed of a rifle bullet).

4. Effusion of Molecules

The number of molecules which effuse through an ideal orifice of unit area per second, v , is given by

$$v = \frac{1}{4} \rho \bar{v},$$

where ρ is the number of molecules per cm^3 , $\bar{v}$ is their average speed.

5. Number of Molecules Striking a Surface

We find that the number of molecules striking a unit area of surface per second is also given by the above equation. If we substitute for ρ and $\bar{v}$, then

$$\nu = 3.513 \times 10^{22} \frac{P \text{ (torr)}}{\sqrt{MT}} \text{ cm}^{-2} \text{ sec}^{-1} ,$$

where M is molecular weight of the gas. For oxygen at 300°K (27°C) and at a pressure of 10^{-6} torr, $\nu = 3.57 \times 10^{14}$ collisions per cm^2 per sec. If each oxygen molecule which hit the surface stuck to it, the surface would be covered with a monolayer of oxygen in about one second. We see that for a fixed temperature the number of collisions with a surface is directly proportional to the pressure. Therefore, by decreasing the pressure, we can increase the length of time it takes for a clean surface to be covered with a layer of gas.

6. Number of Collisions sec^{-1}

The number of collisions one molecule makes per second, Z , is given by

$$Z = \sqrt{2} \pi \rho d^2 \bar{v} ,$$

where πd^2 is the collision cross section, and $\bar{v}$ the average velocity. The quantity d is about equal to the "molecular diameter."

7. Mean Free Path

The mean free path is the average distance a molecule will travel between collisions and is equal to

$$\lambda = \frac{\bar{v}}{Z} = \frac{1}{\sqrt{2} \pi \rho d^2} .$$

8. Variation of λ , ρ , ν , with Pressure

The variations of gas density, mean free path, and collisions with a surface (for "air") as a function of pressure are listed in Table VI.

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TABLE V

Value of the Gas Constant R for Various Units
(from Handbook of Chemistry and Physics 1960)

8.3170×10^7 ergs per °C per mole

1.9869 calories (15°) per °C per mole

<u>Units of Pressure</u>	<u>Units of Volume</u>	<u>R per gram Molecule</u>
Atmospheres	cm ³	82.057
Atmospheres	Liters	0.082057
Atmospheres	Cubic meters	8.2057×10^{-5}
Dynes per cm ²	cm ³	8.3144×10^7
Kilograms per m ² (g = 980.6)	cm ³	8.48×10^5
Torr	cm ³	6.24×10^4
Torr	Liters	62.4

TABLE VI

Variation of Mean Free Path, Density,
and Collisions with Surface with Pressure

Pressure (torr):	760 (1 atm)	1	10^{-3}	10^{-8}	10^{-13}
Density (mol/cc):	2.5×10^{19}	3.2×10^{16}	3.2×10^{13}	3.2×10^8	3.2×10^3
Mean Free Path* (cm):	6.6×10^{-6}	5×10^{-3}	5	5×10^5	5×10^{10}
Collisions with Surface* (mol/sec/cm ²):	2.9×10^{23}	3.8×10^{20}	3.8×10^{17}	3.8×10^{12}	3.8×10^7

*For air at 25°C.

V. THE TRANSPORT OF GASES IN VACUUM SYSTEMS

A. TYPES OF GAS TRANSPORT

In general, the nature of gas transport depends to a large extent on the pressure and the pressure gradients in the system. Three classes of gas transport or flow are turbulent flow, viscous flow, and molecular flow. In turbulent flow the lines of flow are tortuous and the flow is proportional to the square root of the pressure gradient. At lower pressure gradients the lines of flow become lamilar and the flow proportional to the pressure gradient--this is viscous flow. At still lower pressures, where the mean free path of the gas (λ) becomes about equal to the dimensions of the system, we enter the region of molecular flow, or Knudsen flow. The transition regions between these types of flow are somewhat hazy.

We need only be concerned with viscous flow and molecular flow when dealing with vacuum systems. Collisions of molecules with molecules prevail in viscous flow; whereas, collisions of molecules with the walls of the system predominate in molecular flow.

The ratio of mean free path, λ , to a characteristic dimension of the system, a , is called the Knudsen number and is used to characterize the type of gas flow. For example

if $\frac{\lambda}{a} < 0.01$, we have viscous flow;

if $\frac{\lambda}{a} > 1.00$, we have molecular flow; and

if $0.01 < \frac{\lambda}{a} < 1.00$, we have an intermediate kind of flow.

The mean free path of air at 25°C is about equal to

$$\lambda_{(\text{air } 25^{\circ}\text{C})} = \frac{5 \times 10^{-3}}{P \text{ (torr)}} = \text{cm.}$$

Therefore, if $P = 10^{-3}$ torr, the mean free path is 5 cm or 2 inches; and if $P = 10^{-6}$ torr, $\lambda = 5000$ cm or 2000 inches. Thus, for high vacuum systems we have high Knudsen numbers, and molecular flow.

B. IMPEDANCE AND CONDUCTANCE*

Vacuum systems are composed of a variety of components of different sizes and shapes. To design efficient systems, it is important to know how different configurations restrict or aid the transport of gas molecules.

1. Throughput, Q

The flow rate or throughput, Q, is defined as

$$Q = \frac{dV}{dt} P = \dot{V}P \quad ,$$

where $\dot{V}$ is the volume of gas traversing a plane in the system per unit time, and P is the pressure at that plane.

Q is in fact proportional to the number of molecules crossing the plane since

$$Q = \dot{V}P = k \frac{dn}{dt} T = k \dot{n} T \quad .$$

Units are torr liter sec⁻¹.

2. Impedance, Z

The impedance, Z, of any part of the vacuum system is defined as

$$Z = \frac{P_1 - P_2}{Q} \quad ,$$

where $P_1 - P_2$ is the pressure difference across the part. Units are sec liter⁻¹.

3. Conductance, C

The conductance, C, of any part of the system is defined as

$$C = \frac{1}{Z} = \frac{Q}{P_1 - P_2} \quad .$$

Units are liter sec⁻¹.

*See also Appendix A.

4. Parallel C and Z

For parallel arrangements

$$C_p = \sum_i C_i = C_1 + C_2 + C_3 + \dots$$
$$\frac{1}{Z_p} = \sum_i \frac{1}{Z_i} = \frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} + \dots$$

5. Series C and Z

For series arrangements

$$\frac{1}{C_s} = \sum_i \frac{1}{C_i} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots$$
$$Z_s = \sum_i Z_i = Z_1 + Z_2 + Z_3 + \dots$$

6. Electrical Analogy

We see that the relations among Q, P, and Z are very analogous to those between the current, voltage, and resistance in ohmic electrical circuits.

C. MOLECULAR FLOW OF GAS THROUGH AN APERTURE

1. Molecular flow through an ideal aperture: from the kinetic theory equation for the effusion through an ideal orifice (Section IV B4) we calculate the net throughput through an aperture (whose size is less than the mean free path of the molecules) separating volumes (which are much larger than the aperture) at pressures P_1 and P_2 to be

$$\dot{n} = A \cdot \sqrt{\frac{1}{2\pi MRT}} (P_1 - P_2) \text{ molecules sec}^{-1} ,$$

or

$$Q = A \cdot \sqrt{\frac{RT}{2\pi M}} (P_1 - P_2) \text{ torr liter sec}^{-1} ,$$

where A is the area of the aperture in cm^2 . At 20°C this equation becomes

$$Q = \frac{62.5}{\sqrt{M}} (P_1 - P_2) A \text{ torr liter sec}^{-1}.$$

We see that for air (average molecular weight = 29) this expression becomes

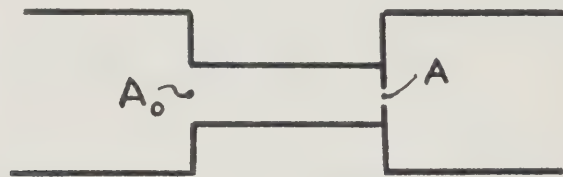
$$Q = 11.6 (P_1 - P_2) A \text{ torr liter sec}^{-1}.$$

Therefore, the conductance, C, of an ideal aperture for air at 20°C is

$$C = 11.6 A \text{ liter sec}^{-1}.$$

Thus, the maximum rate at which air can flow (molecular) through an ideal aperture at 20°C is $11.6 \text{ liter sec}^{-1} \text{ cm}^{-2}$.

2. Molecular flow through a thin large aperture:



The conductance is given by

$$C = C_A \frac{A_0}{A_0 - A}.$$

D. FLOW OF GAS THROUGH A TUBE

1. Molecular Flow - Long Circular Tube

Molecular flow through a long circular tube

$$Q = \frac{1}{6} \sqrt{\frac{2\pi RT}{M}} \frac{d^3}{l} (P_1 - P_2),$$

where d is the diameter in cm of the tube and l is the length in cm.

For air at 20°C we find

$$Q = \frac{12.1 d^3}{l} (P_1 - P_2) \text{ torr liter sec}^{-1}.$$

The conductance is

$$C = 12.1 \frac{d^3}{l} \text{ liter sec}^{-1},$$

or

$$C \sim 100 \frac{r^3}{l} \text{ liter sec}^{-1},$$

where r is the radius in cm.

2. Viscous Flow - Long Circular Tube

Viscous flow through a long circular tube: the conductance for air at 20°C is

$$C = 182 \frac{d^4}{l} \bar{P} \text{ liter sec}^{-1},$$

where $\bar{P}$ is the average pressure in torr.

3. Molecular Flow - Short Circular Tube

Molecular flow through a short tube: here we must include the conductance of the entrance to the tube, i.e., the aperture. Now

$$\frac{1}{C} = \frac{1}{C_{\text{tube}}} + \frac{1}{C_{\text{aperture}}} \quad .$$

For air at 20°C

$$C = 12.1 \frac{d^3}{l} \alpha \text{ liter sec}^{-1},$$

where α depends on l/d . Values for α are given in Table VII.

E. THERMAL TRANSPIRATION

If we have two systems at temperature T_1 and T_2 separated by a small tube or aperture, we find that gas will flow from one to the other (transpiration) until

$$\frac{P_1}{P_2} = \sqrt{\frac{T_1}{T_2}} \quad .$$

This equation is valid if the diameter of the connecting tubing, d , is small to the mean free path, λ . When $d \gg \lambda$, then the pressure in both vessels is the same; however, we find the density varies as:

$$\frac{\rho_1}{\rho_2} = \frac{T_2}{T_1} \quad .$$

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TABLE VII

Values of α for Short Tube Calculations
(Adapted from Guthrie and Wakerling, op. cit.)

<u>1/d</u>	<u>α</u>
0.05	0.036
.08	.055
.1	.068
.2	.13
.4	.21
.6	.28
.8	.30
1.0	.38
2	.54
4	.70
6	.77
8	.81
10	.84
20	.91
40	.95
60	.97
80	.98
100	1.00

VI. PUMPING--THE REMOVAL OF GAS FROM A SYSTEM

A. INTRODUCTION

Gas molecules can be removed from a chamber in a variety of ways. These include pumping by momentum transfer from a moving fluid or gas or surface, condensation or adsorption, chemisorption on an active metal, and ionization and acceleration into a surface. The selection of the method of pumping for a given experiment or system depends on the kind and quantity of gas to be pumped as well as the ultimate pressure that is to be obtained.

B. FUNDAMENTAL CONSIDERATIONS

1. Pumping Speed

Gaede has defined the pumping speed of a pump, S , to be the volume of gas which passes the plane of the pump port (inlet) per unit time, when the pressure at the pump inlet is P , i.e.,

$$S = \frac{Q}{P} .$$

The throughput, Q , can be measured across any plane in the system, but the pressure must be measured at the pump inlet. In general, the speed of a pump is given by

$$S = \frac{(\dot{V}P)}{P} \quad \begin{array}{l} \text{any plane} \\ \text{pump inlet} . \end{array}$$

We can also say that the pumping speed in any plane of a system is equal to the volumetric flow across that plane.

The units of pumping speed are volume sec^{-1} . Table VIII gives relationships among various units for pumping speed.

Loevinger (in Guthrie and Wakerling) points out that while conductance and pumping speed have the same units and are sometimes equivalent numerically, they are never equivalent in meaning. Conductance is to be applied to impedances only, since it implies a pressure gradient and may be looked upon as a geometrical property of the impedance. Pumping speed, on the other hand, can be applied to any plane in the system that may reasonably be considered as a pump for that

part of the system preceding it. Pumping speed may be looked upon as the ability of the system to remove gas and always implies a gas sink.

In practice it is often found that a real pump may act as a source of gas to the vacuum system. Thus, we can characterize a real pump by assigning it a given speed, S_f , and given leak rate, Q_f . The actual amount of gas removed by this pump is equal to

$$Q = S_f P - Q_f = S_f P \left(1 - \frac{Q_f}{S_f P} \right).$$

When $Q = 0$, the ultimate pressure of the pump, P_0 , is reached; therefore $Q_f = S_f P_0$. Therefore

$$\frac{Q}{P} = S = S_f \left(1 - \frac{P_0}{P} \right),$$

where S is the effective pumping speed of the real pump.

The pumping speed of a pump may be measured by a constant pressure method, a constant volume method, and a circulatory method. These are described in Dushman and other books.

2. Effect of Conductance on Pumping Speed

The tubing connecting a pump to a system can have an effect on the speed of the pump. We find that the effective speed of the pump at the system, S_{eff} , is given by

$$\frac{1}{S_{eff}} = \frac{1}{S} + \frac{1}{C},$$

where S is the speed of the pump at its inlet and C is the conductance of the connecting tube. Solving for S_{eff} , we obtain

$$S_{eff} = \frac{SC}{S+C}.$$

If a very fast pump is used, i. e., $S \gg C$, then $S_{eff} = C$. That is, obviously the effective pumping speed can never exceed the rate of gas flow through the connecting tube.

3. Pump Down Time

The time to pump a system of volume V from P_1 to P_2 with a pump of speed S may be estimated by using the expression

$$t = 2.3 \frac{V}{S} \log \frac{P_1}{P_2} \text{ sec,}$$

where V is in liters and S in liter sec^{-1} .

C. MECHANICAL PUMPS

1. Piston Pumps

Piston pumps, used by von Guericke and Boyle and other early workers, have been replaced today by more efficient machines. However, the Toepler pump which uses mercury as a piston is frequently used to pump small quantities of gas in laboratory transfer lines.

2. Rotary Pumps

(a) Eccentric Rotor--Rotary pumps often contain a rotor mounted eccentrically in a stator. Spring loaded vanes and oil films act as seals. The speed of such a pump is equal to the volume swept out by the rotor, V_r , times the frequency of rotation, f , i.e.,

$$S = fV_r.$$

Pumping speeds range from 20 liters min^{-1} to greater than 20,000 liters min^{-1} . Ultimate pressures are in the neighborhood of 10^{-4} torr. A gas-ballast pump is necessary when pumping large quantities of water vapor or volatile liquids. In this pump, air is injected during the compression cycle to prevent the water from condensing.

(b) Roots pumps contain two figure-eight-shaped lobes that rotate in opposite directions against each other. This pump is made with extremely close tolerances and oil is not necessary for sealing. These pumps can have an extremely high pumping speed and can attain ultimate pressures as low as about 5×10^{-6} torr. One model has a speed of 332,000 liter min^{-1} and an ultimate pressure of 10^{-3} torr. Roots pumps usually are used in the pressure range 10^{-3} to 20 torr.

(c) Molecular Pumps--A third class of rotary pump is the molecular pump. Here a high speed rotor transmits momentum to the gas molecules to be pumped in the direction of the exhaust port. There are no mechanical seals between the input and exhaust ports of the pump. Beams has developed a molecular pump in which the rotor is suspended and rotated by magnetic fields. Pumps of this type have been used to attain pressures as low as 6×10^{-7} torr.

D. VAPOR PUMPS

In these pumps momentum is transferred to the gas to be pumped by a directed high speed working fluid or vapor. Water, mercury, and oil have been used as working fluids. These pumps cannot operate against a large pressure difference and usually exhaust to a mechanical pump.

1. Ejector Pumps

Ejector pumps often employ a high velocity jet of steam, oil, or mercury vapor. The mean free path of the pump fluid is normally quite a bit less than the intake port dimension of the pump. These pumps normally have maximum speeds at intake pressures of about 10^{-2} torr and exhaust at pressures of greater than 0.5 torr. These pumps find application in metallurgical, food, chemical, and biological industries because of their high pumping capacities and simplicity.

2. Diffusion-Condensation Pumps

Diffusion-condensation pumps are widely used to achieve very low pressures. They operate over the pressure range of less than 10^{-10} torr to about 2×10^{-2} torr and exhaust to pressures less than 0.5 torr. [The mean free path of pump fluid molecules is greater than the dimensions of the intake port (throat) of the pump.]

Gaede and Langmuir are responsible for the early development of the diffusion-condensation pump. These pumps are commonly referred to as diffusion pumps. The working fluid in a diffusion pump is either mercury or a low vapor pressure oil. The choice of the pump fluid is dependent upon the ultimate pressure desired and the nature of the gas being pumped.

Diffusion pumps normally contain several stages or jet assemblies. This produces a reduced pressure differential across each stage and permits the pump to be used over a wide pressure range.

The theoretical pumping speed of a diffusion pump is equal to the maximum rate of flow of gas across the effective pump inlet (throat) area as calculated for molecular effusion. Real pumps never achieve this speed. The ratio of the actual pumping speed to the theoretical speed is called the speed factor or Ho coefficient. In practice the speed factor is found to equal about 0.45 or less.

The speed of a large diffusion pump is approximately equal to

$$S = 2d^2 \text{ liter sec}^{-1},$$

where d is the diameter of the pump throat in cm. Pumping speeds of diffusion pumps range from a few liters sec⁻¹ to greater than 20,000 liters sec⁻¹.

Both oil and mercury are used as working fluids in diffusion pumps. Because oils contain a range of molecular weight compounds and will decompose at boiler temperatures, the jet assembly in oil diffusion pumps is often arranged to fractionate the oil. The more volatile oil components (and dissolved gases) issue from the lower jets (those near the mechanical pump), and higher molecular weight components exit through the top jet. This means that the fractionating pump can achieve a lower ultimate pressure than its nonfractionating counterpart.

The working fluid in diffusion pumps can diffuse into the system being evacuated. This is called back streaming. Back-migration also occurs. This is the evaporation of the working fluid from the internal parts of the pump near the throat.

Cooled baffles and traps are used to reduce these two sources of gas. Charcoal, zeolites, alumina, liquid nitrogen, and outgassed OFHC copper are often used as trap materials.

E. BAFFLE AND TRAP DESIGN

1. Mechanical Pumps

Mechanical pumps are normally separated from diffusion pumps by liquid nitrogen traps or phosphorous pentoxide traps. The former helps keep oil from migrating to the diffusion pump, and the latter prevents water vapor from entering the mechanical pump. In ultrahigh vacuum systems it is very

important to isolate the mechanical forepump from diffusion pumps with a liquid nitrogen trap.

2. Diffusion Pumps

Cooled baffles are normally installed above the top jet assembly in diffusion pumps to reduce or prevent back streaming. Chilled water, freon, or liquid nitrogen are used to cool the baffles. Baffles are designed to present an optically dense path to back streaming pump fluid molecules, i.e., molecules must collide with the baffle at least once before entering vacuum system. They are also designed to reduce the pumping speed as little as possible. Even cooled baffles will not completely stop back-migration of oil molecules.

Traps containing oxygen-free high-conductivity copper (OFHC-copper) have been used by Alpert and others to prevent the migration of oil molecules into the vacuum system. These traps are very efficient when well outgassed and have made it possible to achieve pressures in the 10^{-10} torr range with oil diffusion pumps.

Traps containing zeolites or alumina were developed by Biondi and Harris. These devices, when well outgassed, are efficient sinks for oil molecules and like the copper trap permit oil pumps to produce pressures in the 10^{-10} torr range.

It is necessary to use liquid nitrogen traps with mercury diffusion pumps. The vapor pressure (27°C) of mercury is about 10^{-3} torr; however, at -196°C (the temperature of liquid nitrogen) the vapor pressure of mercury is negligible (estimated to be less than 10^{-30} torr). The condensation coefficient of mercury is close to unity at these temperatures.

All traps offer some impedance to the flow of gas and reduce the effective pumping speed of the pump.

F. CRYOGENIC PUMPS

1. Condensation and Adsorption

In principle the simplest method for removing gas from a volume is to adsorb or condense it on the walls of the vessel by reducing the temperature. If the gas is removed by condensation on a very cold surface (such that its vapor

pressure is negligible), the term cryogenic pumping or cryo pumping is applied. If, however, the gas is physically adsorbed on a material of high surface area at a lower temperature, the term sorption pumping is usually applied.

Sorption pumps consisting of a tube of activated charcoal at liquid nitrogen temperature have been used for years. Today zeolites have been used as well as charcoal. Such pumps are often used in place of mechanical pumps in the initial pump down of ultrahigh vacuum systems.

The vapor pressures of the common gases at a variety of temperatures are tabulated in Table IX and given graphically in Fig. 1. We see that at 20°K (the boiling point of hydrogen at 760 torr) all gases except helium, hydrogen, and neon have a negligible vapor pressure. At 4.2°K (the boiling point of liquid helium at 760 torr) all gases but helium have a very low vapor pressure. Therefore, cold surfaces at these low temperatures will act as pumps for most of the common gases.

The rate of removal of a gas depends on the condensation coefficient for the gas at the temperature of the surface and the cold surface area available. The condensation coefficient, β , is the fraction of molecules that stick to the surface divided by the number that struck the surface.

The pumping speed of a surface, S_S , of area A for a condensable gas may be easily calculated from the equation given in V-C for the molecular flow through an aperture. We see that

$$Q = A \cdot \sqrt{\frac{RT}{2\pi M}} (P_1 - P_2).$$

Rearranging we obtain

$$\frac{Q}{P_1 - P_2} = C_S = S_S = \sqrt{\frac{RT}{2\pi M}} \times A,$$

where T is the temperature of the gas, M its molecular weight, and S_S the pumping speed of an aperture or a cold surface. For $T = 27^\circ\text{C}$, and A in cm^{-2} , we obtain

$$S_S = \frac{63}{\sqrt{M}} \times A \text{ liter sec}^{-1}.$$

If the gas being pumped is water, then $S_S = 14.8 \times A \text{ liter sec}^{-1}$.

Hobson has estimated that extremely low pressures; i.e., $P \leq 10^{-20}$ torr, can be achieved by cooling an ultrahigh vacuum system to 4.2°K.

It is possible to achieve enormous pumping speeds with cryogenic pumps. Therefore, they are being used in large space simulators.

2. Ice Pumping

Ice pumping or cryotrapping is the term applied to the removal of a non-condensable gas, A, by the rapid condensation of a condensable gas, B. Gas A is apparently trapped in the solid matrix of gas B as gas B condenses on a cold substrate. Experiments by Brackman and Fite show that a system initially evacuated with a water aspirator and finally pumped by water vapor condensing on a surface (cooled with liquid nitrogen), can be evacuated to a pressure of about 5×10^{-5} torr. They speculate that this "represents probably the world's least expensive method of producing a vacuum, for the total cost of the equipment is less than ten dollars."

G. CHEMISORPTION PUMPS

It is often convenient to remove chemically-active gases from a vacuum system by reacting them with an active metal to form a compound with a very low vapor pressure, or a strongly held chemisorbed layer of gas. Pumps of this type have been used for many years in the production of vacua in radio tubes and other electronic devices and are usually referred to as getters. Similarly the process of chemisorption or reaction of the metal with the gas is called gettering.

In these pumps, active metal films are usually generated by the evaporation of a wire or pellet by resistance heating, or by radio frequency induction heating. Of course, the bulk getter must be carefully outgassed before evaporation or it will contribute gas to the vacuum system.

Often, a metal will adsorb only a limited variety of gases. Thus, by judicious choice of a getter material trace impurities may be removed from a gas. Table X lists a number of metals and semimetals and the gases that they will chemisorb at room temperature.

Clean metals can also alter the composition of gas in a system. For example, Roberts has found that ethane, propane, and butane will decompose on

clean films of rhodium and iridium to methane. Holland has reported that when impure titanium getters were heated and evaporated in vacuum, methane was formed from hydrogen and carbon impurities.

Titanium, molybdenum, and barium have been used extensively as getter materials.

The speed of getter pumps depends primarily on the effective surface area of the getter and the sticking coefficient of the gas.

H. ELECTRONIC PUMPS

Electronic pumps remove gas from a system by ionizing gas molecules by electron impact and by accelerating the positive ions formed through several thousand volt potential difference into a metal or glass surface. The adsorption and re-emission of ions from metal and glass surfaces has been investigated by many workers.

Alpert used the inverted or Bayard-Alpert ionization gauge as a pump. Such a gauge operating with 10 ma electron emission current, grid at 150 v, collector at -20 v has a pumping speed of about $0.1 \text{ liter sec}^{-1}$.

I. ELECTRONIC-CHEMISORPTION PUMPS

These pumps are very effective devices for evacuating a system. They can pump chemically active and inactive gases, do not act as a source of contaminating gases, and do not require liquid nitrogen traps.

These pumps contain a means for producing fresh metal surfaces, a source of electrons, and an accelerating field. The potential of the fresh metal surface is negative. Titanium and molybdenum are normally used for the getter material.

Several means have been used for producing clean metal films. These include evaporation from a wire source, evaporation by electron bombardment, or sputtering.

Alpert has used an ionization gauge that incorporates a tungsten filament overwound with titanium as an effective pump. He has measured pumping speeds of $20 \text{ liter sec}^{-1}$ for nitrogen.

In the "Evapor-ion" pump titanium wire is fed onto a tungsten post, which is heated to a high temperature by electron bombardment. Pumping speeds of $8000 \text{ liter sec}^{-1}$ were measured for hydrogen at 3×10^{-6} torr. The speed for argon was about 9 liter sec^{-1} at 4×10^{-6} torr.

Kornelsen has developed a small inverted-magnetron pump which employs an evaporated titanium getter. This pump has a pumping speed of $0.03 \text{ liter sec}^{-1}$ for helium, $0.25 \text{ liter sec}^{-1}$ for argon, and 1 liter sec^{-1} for nitrogen. This has been used very successfully in small (5-liter) glass ultrahigh vacuum systems.

Perhaps the most popular type of electronic-chemisorption pump is the sputter-ion pump. This pump was developed by Hall and is based on the cold-cathode or Penning discharge gauge. In its typical form, this pump consists of two parallel-plate titanium cathodes separated by an "egg-crate" shaped anode and located in a magnetic field. Several thousand volts are applied between the anode and the cathodes. Because of the magnetic field, electrons produced travel long spiral paths and have an increased chance of ionizing the residual gas. Positive ions produced are accelerated into the cathodes and sputter titanium onto the high surface area anode. The pumping action is a combination of gettering, acceleration of ions into surfaces, and burial of atoms.

Various refinements of this pump have been developed. These include the slotted cathode pump and the third-electrode pump.

These pumps are available commercially and have speeds which range from 1 liter sec^{-1} to several thousand liters sec^{-1} .

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TABLE VIII

Conversion Table for Units of Pumping Speeds(adapted from Pirani and Yarwood, op. cit.)

<u>Unit</u>	<u>cm³ sec⁻¹</u>	<u>liter sec⁻¹</u>	<u>liter min⁻¹</u>	<u>ft³ min⁻¹</u>
cm ³ sec ⁻¹	1	0.001	0.060	0.0021
liter sec ⁻¹	1000	1	60	2.12
liter min ⁻¹	16.67	0.0167	1	0.0353
ft ³ min ⁻¹	471.95	0.4719	28.32	1

Note: 1 ft³ = 28.316 liters

1 liter = 0.035316 ft³

TABLE IX

Vapor Pressure Data for Some Common Gases
[from R. E. Honig and H. O. Hook, RCA Review, 21, 360 (1960)]

SYMBOL	COMPCIND	REF.	DATA TEMP. RANGE, °K	TEMPERATURES (°K) FOR VAPOR PRESSURES (torr)																
				10 ⁻¹³	10 ⁻¹²	10 ⁻¹¹	10 ⁻¹⁰	10 ⁻⁹	10 ⁻⁸	10 ⁻⁷	10 ⁻⁶	10 ⁻⁵	10 ⁻⁴	10 ⁻³	10 ⁻²	10 ⁻¹	1	10 ¹	10 ²	10 ³
Ar	ARGON	5	82-88	20.3	21.3	22.5	23.7	25.2	26.8	28.6	30.6	33.1	35.9	39.2	43.2	48.2	54.4	62.5	73.4	89.9
Br ₂	BROMINE	1	253-331	102.0	106.5	111.0	116.5	122.0	128.5	135.5	143.5	152.5	163.0	174.5	188.5	204.	224.	248.	282.	339.
CH ₄	METHANE	6,7	48-112	24.0	25.3	26.7	28.2	30.0	32.0	34.2	36.9	39.9	43.5	47.7	52.9	59.2	67.3	77.7	91.7	115.0
CO	CARBON MONOXIDE	1	56-133	20.5	21.5	22.6	23.8	25.2	26.7	28.4	30.3	32.5	35.0	38.0	41.5	45.8	51.1	57.9	67.3	84.1
CO ₂	CARBON DIOXIDE	7,8	107-196	59.5	62.2	65.2	68.4	72.1	76.1	80.6	85.7	91.5	98.1	106.0	114.5	125.0	137.5	153.5	173.0	198.0
COS	CARBONYL SULFIDE	9	162-224													(124.5) 139.5	159.5	187.0	229.	
CS ₂	CARBON DISULFIDE	1	194-319												(160.0) 177.5	199.5	228.	269.	329.	
Cl ₂	CHLORINE	1,10	162-420	66.1	69.1	72.4	76.0	80.0	84.4	89.4	95.1	101.5	109.0	117.5	127.5	140.0	155.0	173.0	201.	245.
F ₂	FLUORINE	11	54-89														(52.2) 59.5	70.5	87.5	
H ₂	HYDROGEN	12	14-21	2.67	2.83	3.01	3.21	3.45	3.71	4.03	4.40	4.84	5.38	6.05	6.90	8.03	9.55	11.70	15.10	21.4
HBr	HYDROGEN BROMIDE	1,13	120-205	51.8	54.3	57.1	60.2	63.7	67.6	72.1	77.1	82.9	89.6	97.5	107.0	118.5	132.5	151.0	175.0	209.
HCl	HYDROGEN CHLORIDE	1	132-195	49.7	52.1	54.6	57.5	60.6	64.1	68.1	72.5	77.6	83.4	90.1	98.1	108.5	121.0	137.0	158.5	193.0
HF	HYDROGEN FLUORIDE	14	240-290														(179.0) 207.	245.	301.	
H ₂ O	WATER	1,15	175-380	113.0	118.5	124.0	130.0	137.0	144.5	153.0	162.0	173.0	185.0	198.5	215.	233.	256.	284.	325.	381.
H ₂ S	HYDROGEN SULFIDE	1,16	153-213	57.1	59.8	62.7	65.9	69.5	73.5	78.0	83.1	89.0	95.7	103.5	113.5	124.5	138.5	156.5	180.5	218.
He	HELIUM	17	0.9-5.2													0.980	1.268	1.738	2.634	4.518
I ₂	IODINE	3	298-456	141.5	147.5	154.0	161.5	169.5	178.5	188.5	199.5	212.	226.	243.	262.	285.	312.	345.	389.	471.
Kr	KRYPTON	5,18	63-121	27.9	29.4	30.9	32.7	34.6	36.8	39.3	42.2	45.5	49.4	53.9	59.4	66.3	74.8	85.9	101.0	123.5
N ₂	NITROGEN	1,19	54-128	18.1	19.0	20.0	21.1	22.3	23.7	25.2	27.0	29.0	31.4	34.1	37.5	41.7	47.0	54.0	63.4	80.0
N ₂ O	NITROUS OXIDE	20	103-186	55.8	58.3	61.1	64.2	67.6	71.3	75.5	80.3	85.7	91.9	99.0	107.5	117.5	129.5	144.0	162.5	189.5
NO	NITRIC OXIDE	1	73-180	37.7	39.4	41.3	43.4	45.6	48.1	50.9	54.0	57.6	61.6	66.3	71.7	78.1	85.7	95.0	106.5	123.5
NH ₃	AMMONIA	21	145-240	70.9	74.1	77.6	81.5	85.8	90.6	95.9	102.0	108.5	116.5	125.5	136.0	148.0	163.0	181.0	206.	245.
Ne	NEON	22	15-45	5.50	5.79	6.11	6.47	6.88	7.34	7.87	8.48	9.19	10.05	11.05	12.30	13.85	15.80	18.45	22.1	27.5
O ₂	OXYGEN	1,23	57-154	21.8	22.8	24.0	25.2	26.6	28.2	29.9	31.9	34.1	36.7	39.8	43.3	48.1	54.1	62.7	74.5	92.8
SO ₂	SULFUR DIOXIDE	1,24	178-263	78.9	82.4	86.3	90.4	95.1	100.0	106.0	112.5	119.5	128.0	137.5	148.5	161.5	177.0	195.5	225.	269.
Xe	XENON	5	110-166	38.5	40.5	42.7	45.1	47.7	50.8	54.2	58.2	62.7	68.1	74.4	82.1	91.5	103.5	118.5	139.5	170.0

NOTE: ○ indicates melting point; \ indicates a phase transition point.

TABLE X
Classification of Metals and Semi-Metals Based on
Adsorption Properties

(A indicates Adsorption, NA No Adsorption)

[from G.C. Bond, Catalysis by Metals, N.Y. Academic Press (1962)]

Metals	Gases						
	O ₂	C ₂ H ₂	C ₂ H ₄	CO	H ₂	CO ₂	N ₂
Ca, Sr, Ba, Ti, Zr, Hf, V, Nb, Ta, Cr, Mo, W Fe*, (Re)	A	A	A	A	A	A	A
Ni, (Co)	A	A	A	A	A	A	NA
Rh, Pd, Pt, (Ir)	A	A	A	A	A	NA	NA
Al, Mn, Cu, Au [†]	A	A	A	A	NA	NA	NA
K	A	A	NA	NA	NA	NA	NA
Mg, Ag*, Zn, Cd, In, Si, Ge, Sn, Pb, As, Sb, Bi	A	NA	NA	NA	NA	NA	NA
Se, Te	NA	NA	NA	NA	NA	NA	NA

* The adsorption of N₂ on Fe is activated, as is the adsorption of O₂ on Ag films sintered at O₂.

† Au does not adsorb O₂.

() Metal probably belongs to this group, but the behavior of films is not known for all gases.

Fig. 1(a) Vapor pressure data for some common gases [from R. E. Honig and H. O. Hook, RCA Review, 21, 360 (1960)].

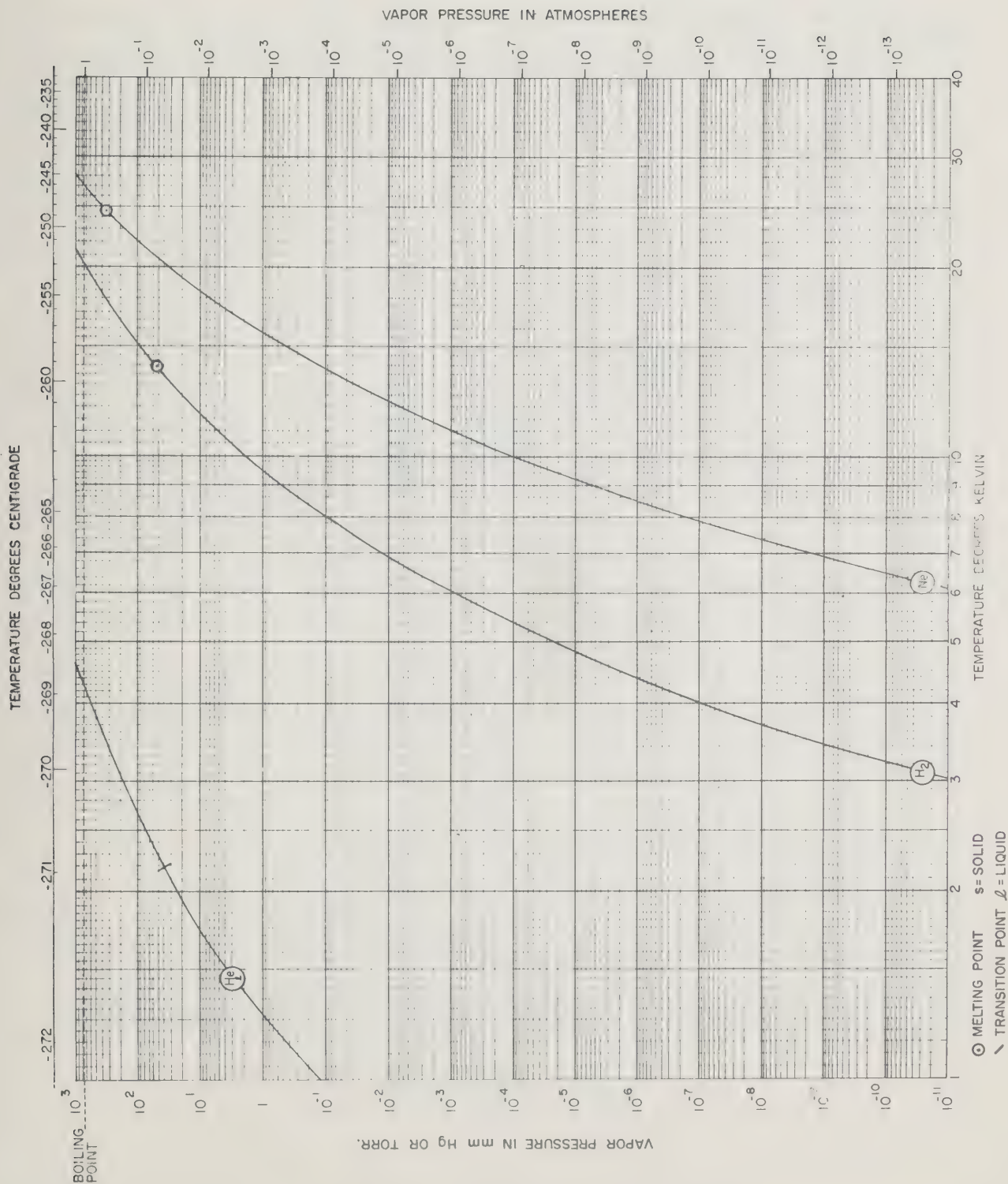
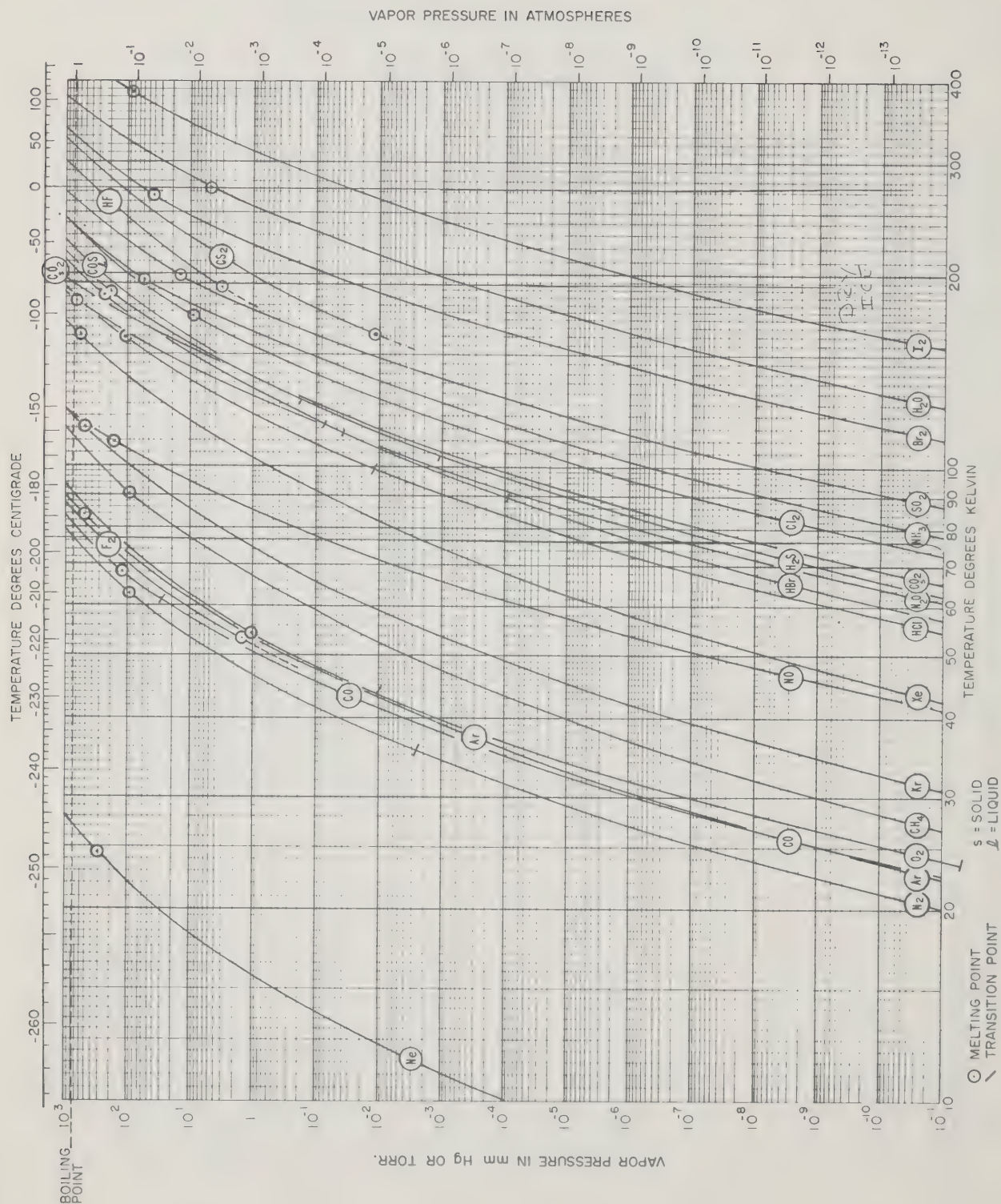


Fig. 1(b) Vapor pressure data for some common gases [from R.E. Honig and H.O. Hook, RCA Review, 21, 360 (1960)].



VII. GAUGES--THE MEASUREMENT OF GAS PRESSURE OR DENSITY

A. INTRODUCTION

In most systems the degree of vacuum is expressed in terms of the total gas pressure in the system. What we are really interested in, for the most part, is the particle density in the system. By knowing the temperature and the pressure, the density may be easily calculated. The composition of the gas in the system is normally expressed in terms of the partial pressure of each component. There are a variety of gauges that will measure the total or partial pressure or density of gas in a vacuum system. The types of gauges and the pressure range in which they function are given in Fig. 2.

B. TOTAL PRESSURE GAUGES

Total pressure gauges sometimes measure the pressure in a system in an absolute fashion. Other varieties of gauges measure a quantity which is proportional to the gas pressure or density. The latter type must be calibrated against the former.

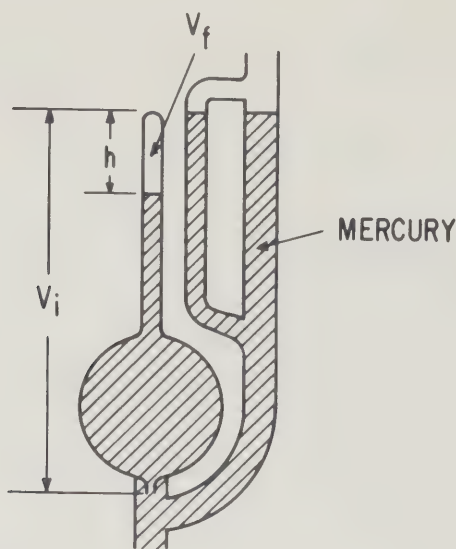
1. Absolute Gauges

(a) A U-tube manometer containing mercury or a low vapor pressure oil is a simple convenient device for measuring pressures in the range 760 torr to about 10^{-2} torr. The sensitivity of such a manometer increases as the density of the working fluid decreases, i.e., an oil-filled manometer is more sensitive than a mercury-filled one. These manometers may be used in conjunction with ultrahigh vacuum systems if they are well trapped. This gauge is independent of the composition of the gas.

(b) The McLeod gauge is the standard device used to calibrate most vacuum gauges. In this gauge, the gas at an unknown pressure is trapped in a standard volume V_i and is compressed to a final pressure P_f , by a mercury piston into a capillary tube of known dimensions. The final volume, V_f , is measured and the initial pressure is calculated from Boyle's Law (see page 13).

$$P_i = \frac{P_f V_f}{V_i} .$$

A typical McLeod gauge that is set to measure a pressure looks like



We see the gas is compressed to a pressure $(P_i + h)$ in the closed capillary of cross section area $a \text{ cm}^2$. Therefore:

$$P_i V_i = (P_i + h) ah, \text{ and}$$

$$P_i = \frac{ah^2}{V_i - ah} \quad .$$

Normally $V_i \gg ah$ and we finally obtain for the unknown pressure

$$P_i = \frac{ah^2}{V_i} \quad .$$

The quantities a and V_i may be obtained by carefully measuring the gauge during its construction. The reading of a McLeod gauge is independent of the gas composition. McLeod gauges may be used to measure pressures down to about 1×10^{-6} torr.

(c) Null manometers incorporate a flexible partition (diaphragm) which separates a region of unknown pressure from a known pressure. The unknown pressure is measured by increasing the known pressure until the diaphragm returns to an equilibrium zero position. Sensitive optical or electrical devices have been used to accurately determine the position of the diaphragm. These

devices have been used to measure pressures in the range 1000 torr to 10^{-3} torr.

(d) The Knudsen gauge depends on the rate of transfer of momentum by molecules traveling from a hot surface to a cold surface. This phenomenon is pressure dependent and may be used to measure pressures in the range of 10^{-2} to 10^{-8} torr. The sensitivity of the Knudsen gauge is probably independent of the gas composition and in principle may be calculated from the geometry of the gauge. No fluids are used.

2. Viscosity Gauges

Viscosity gauges of one type depend on the rate of damping of a vibrating fiber or an oscillating disc. Other devices measure the transfer of momentum from a rapidly rotating disc to a closely spaced disc. Beams has used the deceleration of a magnetically levitated spinning ball bearing to measure the pressure.

3. Thermal Conductivity Gauges

Thermal conductivity gauges measure the rate at which heat is lost from a solid to a surrounding gas. This rate of heat loss depends on the pressure and nature of the gas, and therefore, such gauges must be calibrated for each kind of gas to be measured.

A thermocouple gauge contains a small thermocouple welded to the center of a heated platinum strip. For a fixed current ($\sim 50\text{ma}$) passing through the strip, we find the lower the pressure, the higher the temperature of the strip.

The Pirani gauge consists of a fine heated wire located in the vacuum system. This wire is connected to a sensitive bridge circuit. Changes in pressure are reflected as changes in the temperature (and therefore resistance) of the wire and result in an unbalancing of the bridge.

Thermistor gauges replace a hot wire with a hot bead thermistor. Again a sensitive bridge circuit is used.

These gauges are useful over the range 10^{-4} torr to 1 torr.

4. Ionization Gauges

Ionization gauges represent a different approach toward measuring the pressure (i.e., density) in a vacuum system. These devices convert a fixed portion of the gas molecules to ions and measure the resulting positive ion current. The probability of ionization of a gas molecule depends on a great many parameters; however, these gauges can be calibrated against a suitable standard (i.e., McLeod). A number of approaches have been used to ionize the gas molecules.

(a) The triode ionization gauge is the device used most frequently to measure total pressures in high vacuum systems. Typically this gauge contains a hot tungsten filament (0v potential) as a source of electrons, a grid at $\sim 150\text{v}$, and a collector at $\sim -20\text{v}$. We find that the pressure in a system (as measured by an ionization gauge) can be expressed as

$$P = \frac{1}{S} \frac{i_c}{i_g} ,$$

where S is the sensitivity of the gauge for the particular gas, i_c is the collector or positive ion current, and i_g is the grid or electron current. A list of the relative sensitivities of ionization gauges for a number of gases is given in Table XI. For ionization gauges, $S \approx 13$ for nitrogen.

One of the early forms of the triode ionization gauge took the form of a central filament surrounded by a cylindrical grid and a cylindrical sheet plate. The lower pressure limit of this structure, about 10^{-8} torr, was determined by the x-ray effect. That is, electrons that strike the grid cause the emission of soft x-rays. These x-rays strike the collector plate and produce electrons. The departure of an electron from the plate is electrically the same as the arrival of a positive ion at the collector. This limiting x-ray effect depends to a large extent on the physical shape of the collector. When the collector is massive and surrounds the grid, it intercepts practically all the soft x-rays generated at the grid.

Bayard and Alpert changed the geometry of the ionization gauge to reduce this effect. They inverted the standard gauge structure. Now the

collector takes the form of a 0.005-inch-diameter wire surrounded by a cylindrical grid. Tungsten filaments are located outside the grid. The plate intercepts only a small fraction of the soft x-rays and the lower pressure limit is reduced to about 10^{-10} to 10^{-11} torr. This structure is called the Bayard-Alpert gauge or the inverted ionization gauge.

Ionization gauges with these structures and electron emission currents of 1 to 10 ma are usually not used at pressures greater than 10^{-5} torr.

Schulz, however, reduced the electron current to 100 μ a in a Bayard-Alpert gauge and was able to measure pressures up to about 10^{-1} torr for Ar, He, Ne, H₂, N₂, and SF₆.

Schulz and Phelps modified the ionization gauge so that it had a closely spaced planar structure. This gauge could be used for measuring pressures up to about one torr.

(b) Houston used an axial magnetic field to greatly increase the path length of electrons emitted by a hot filament and thereby increased its sensitivity. The low pressure limit (i.e., x-ray limit) of this gauge is thought to be about 10^{-15} torr. The positive ion current in this device was proportional to the pressure at pressures less than 10^{-8} torr.

(c) Lafferty has developed a hot-cathode magnetron gauge, which operates with very low electron emission currents. With a photomultiplier detector, it is claimed that this gauge will measure total pressures as low as 10^{-16} torr. It has been used to measure pressures as low as 10^{-12} torr.

(d) Cold cathode--A variety of cold cathode ionization gauges have been developed. Practically all of these employ a magnetic field to increase the path length of the ionizing electrons.

The Penning gauge consists of two flat parallel cathodes separated by a cylindrical or ring-shaped anode located in an axial magnetic field. A potential of several thousand volts is applied between the electrodes. Because of the magnetic and electric field, electrons produced by cold emission oscillate in spiral paths between the cathodes. Positive ion current to the cathode is

measured and is proportional to the pressure. Gauges of this type have been used for many years, and can measure pressures from the ultrahigh vacuum range ($\sim 10^{-10}$ torr) to about 10^{-4} torr. These gauges have a fairly high pumping speed. This property was put to use in the sputter-ion pump described earlier.

Redhead and Hobson have developed an inverted magnetron and a magnetron cold cathode gauge that are capable of measuring pressures as low as 10^{-13} torr. These gauges have high pumping speeds and are often used as pumps.

(e) Ultraviolet source--An ionization gauge has been developed at Westinghouse that used an ultraviolet source - photomultiplier as a "cold" source of ionizing electrons. This gauge appears to be linear over the pressure range 10^{-5} to 10^{-10} torr.

(f) Alphatron--The Alphatron gauge uses the alpha particle emission from a radioactive source (radium and its decomposition products) to ionize gas molecules. A commercial gauge of this type will measure pressures in the range 1000 torr to 10^{-3} torr.

5. Surface Sensitive Phenomena

There are a number of surface sensitive phenomena that have been used to estimate the pressure (of an adsorbable material) in very high vacuum systems. These include flash filament, field emission, emission from cathodes, Auger neutralization of ions, and work function measurements.

C. PARTIAL PRESSURE GAUGES

1. Introduction

Partial pressure gauges are usually called mass spectrometers, which convert a portion of the gas into ions and measure the relative number of ions of each mass (or mass/charge, m/e) present. Mass spectrometers usually contain (1) an inlet system for the gas to be measured, (2) an ionization region in which the gas is converted to ions, (3) an analyzing region that separates the ions according to their m/e ratio, and (4) a detector that measures the number of ions of each m/e ratio.

Ionization is usually accomplished by bombardment with electrons from a hot filament, although, cold cathode, spark sources, field ionization, and other sources have been used. Detectors are either Faraday cage collectors or ion multipliers. The latter detector is generally used at very low pressures, i.e., low ion concentrations. The types of $\frac{m}{e}$ analyzers vary greatly. We shall discuss the more common ones in the following paragraphs.

2. Magnetic Deflection Mass Spectrometer

The magnetic deflection mass spectrometer is perhaps the most widely used device for partial pressure measurement in vacuum systems. Ions produced by electron bombardment are accelerated through a potential difference and analyzed with a magnetic field. When the ions enter the magnetic field they experience an acceleration and have circular trajectories with a radius r . This radius of curvature is a function of the mass of the ion, m ; its charge, e ; its energy, Ve ; and the magnetic field strength, H . Here V is the potential difference, and e is equal to ne' , where e' is the charge of an electron and n the number of such charges. We find that the radius is given by

$$r = \frac{\sqrt{2Vm/ne'}}{H}, \text{ or}$$

$$r = \frac{144}{H} \sqrt{VM/n},$$

where M is the molecular weight of the ion.

The magnet may deflect the ions through an angle of 60° , 90° , or 120° .

With sensitive photomultiplier detectors and counting devices, these mass spectrometers will operate in extreme ultrahigh vacuums.

3. Pulsed Beam, Time-of-Flight

Perhaps the simplest mass spectrometer device is the pulsed beam time-of-flight spectrometer. In this instrument the gas is ionized and is accelerated through a potential drop; however, the accelerating potential is applied in an a-c manner so that pulses or bunches of ions of the same energy

are produced. These pulses enter a tube (flight tube) and the rate of arrival at a detector at the end of the tube is measured. The transit time t depends on the length of the tube, L , and the velocity, $\bar{v}$; that is:

$$t = \frac{L}{\bar{v}} ,$$

but

$$\bar{v} = \sqrt{\frac{2Ve}{m}} ,$$

where V is the potential difference, e the charge of the ion, and m , the mass of the ion. Thus

$$t = L \sqrt{\frac{m}{2Ve}} .$$

The Bendix Aviation Corporation sells a mass spectrometer that operates on this principle. The flight tube is about one meter long and produces about 10,000 pulses per second.

4. Radiofrequency Mass Spectrometer

A radiofrequency mass spectrometer has been developed by Boyd, Bennett, and Redhead. In this device the gas is ionized, accelerated to high velocity and is sent through an analyzing region which is composed of a series of equipotential fields, an rf electrode system. The gain in energy of the ions is a sharp function of their charge to mass ratio. We find that an ion will remain synchronous with the applied fields if the transit time between alternate grids is equal to the half period of the applied rf voltage. If a synchronous ion enters the analyzer at the proper phase angle with the rf field, it will receive a maximum energy increase and will therefore reach a collector placed behind a d-c retard-ind field. The mass to charge ratio of ions that will traverse the analyzer is given by

$$\frac{m}{e} \propto \frac{V}{S^2 f^2} ,$$

where V is the d-c accelerating voltage, S is the spacing of the grids, and f is the frequency.

5. Omegatron

The omegatron is a very small compact device, which has found wide application as a partial pressure measuring device in vacuum technology. The operation of the omegatron is somewhat similar to that of a cyclotron. Ions are created in the center of a small box located in a homogeneous magnetic field of strength H . An rf potential is applied across two ends of the box. The time for an ion of mass to charge ratio m/e to make one revolution in the box is

$$t = \frac{2\pi m}{He}.$$

If the ion is to revolve continuously in the box and eventually be collected near one side, then the applied frequency, w , must have the same period. That is,

$$w = \frac{2\pi}{t} = \frac{He}{m}.$$

Thus by measuring the collector current as a function of w , we obtain a mass spectra of the gas in the device.

Such devices are very inexpensive to construct but can not be used to detect masses much above 50 or so.

6. Crossed-Field

A crossed-field mass spectrometer has been used to a limited extent in high vacuum systems. In this spectrometer ions are formed and accelerated into an analyzer consisting of mutually perpendicular uniform magnetic and electric fields. In this device ions follow a trochoidal path. Regardless of the initial velocity (i.e., speed and direction), all ions from the source are focused to a point; therefore, the ion collection efficiency can be very high.

7. Quadrupole or Monopole

The quadrupole mass spectrometer and monopole mass spectrometer are relative newcomers to mass spectrometry. The quadrupole mass spectrometer separates ions with different m/e by means of an rf electric field, the potential of which is a quadratic function of the coordinates x and y . Four

rods with a circular or hyperbolic cross section are used to create the field. In the monopole variation, a part of this field is created by two electrodes, one being a circular rod and the other a right angle.

D. GAUGE CALIBRATION

1. Introduction

In order to convert the measurement of the height of a column of liquid or the number of positive ions produced per second into gas pressure or density, we must multiply by conversion factors. The determination of these factors is accomplished by calibrating the device. A variety of calibration procedures have been developed. These depend on the gauge and the pressure range involved.

2. U-Tube

To convert height differences in a U-tube manometer to pressure, the variation of the cross sectional area must be known and the density of the working fluid must be known. In general, precision bore tubing is used so that the variation of area is very small. The density of the working fluid can be measured by weighing a known volume of fluid.

3. McLeod

In order to calibrate a McLeod gauge the initial volume V_i , and the cross sectional area of the capillary tubing must be measured. The gauge is first weighed. Then it is filled with water to the cut off point and weighed again. By dividing the weight difference by the density of water at that temperature, V_i is calculated. The average cross sectional area of the capillary is found by measuring the length of a weighed bead of mercury at different positions along the tube. If the tube has a uniform bore, the length of the bead should not vary as a function of position. The cross sectional area of the capillary is equal to the weight of the mercury bead divided by its length times the density of mercury.

It is very important, for low pressure measurements, that the dimensions of the top of the capillary are not altered during the sealing-off and that the top be flat.

4. Ionization Gauge

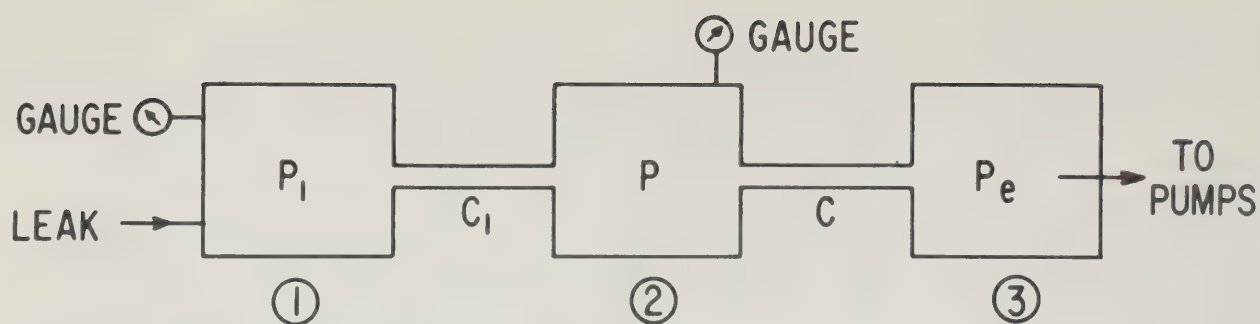
The accurate calibration of ionization gauges over their entire range of calibration is a difficult task. A number of approaches have been used.

(a) Direct--The ionization gauge may be compared directly with a McLeod gauge over the range of about 10^{-3} to 5×10^{-5} torr with a permanent gas. The system must be well outgassed. The McLeod gauge must be separated from the system by a liquid nitrogen or dry ice trap (as the vapor pressure of mercury at room temperature is about 10^{-3} torr). Care must be taken to keep the conductances large so that no pressure gradients develop. Remember that the ion gauge acts as a pump.

(b) Pressure rise--The problem remains - how can the gauge calibration be extended to pressures below about 10^{-5} ? Alpert established that the response of an ion gauge is linear with pressure down to about 10^{-10} torr. He did this with a pressure rise technique. Gas was leaked into a vessel containing the gauge such that the pressure rose as the time squared. Now the calibration curve measured with the McLeod down to 10^{-5} torr may be extrapolated linearly to about 10^{-10} torr.

(c) Pressure expansion--The pressure expansion technique introduced by Knudsen is simple method for producing a low pressure of known value. Here a known volume is filled to a known pressure (McLeod gauge). The gas is then expanded into a large calibrated volume. The final pressure is calculated using Boyle's Law. It appears that this method is applicable in producing pressure as low as 10^{-7} torr. At low pressures, adsorption and desorption of gas on the walls can cause large errors.

(d) Calibrated conductance--The calibrated conductance method appears to be a convenient way of accurately generating reproducible pressures. This method is shown schematically as follows:



The pressure in vessel (1) is controlled by altering the leak and measured with a manometer. Vessel (1) is connected via conductances C_1 and C to a pump that can maintain a low equilibrium pressure P_e . P is the pressure at the junction of the two conductances. The gas flow rate in the system, Q , is

$$Q = C_1 (P_1 - P) = C(P - P_e).$$

Now

$$C_1 = \left(\frac{\pi RT}{2M} \right)^{1/2} K_1, \text{ and}$$

$$C = \left(\frac{\pi RT}{2M} \right)^{1/2} K,$$

where K_1 and K are factors depending on the geometry of the conductances. Solving for P , we obtain

$$P = \frac{K_1 P_1 + K P_e}{K_1 + K}.$$

Thus, P is independent of M and T . In practice $P_1 \gg P_e$ and

$$P = \frac{K_1}{K_1 + K} P_1.$$

(e) Field emission--The field emission microscope has also been used to calibrate an ionization gauge. Here the time required for a clean tungsten field emission pattern to be completely modified was used to indicate the pressure. This does not appear to be a very practical method.

5. Successive Isotopic Ratio

Mass spectrometers have been calibrated at very low pressures by using the method of successive isotopic ratio measurements.

E. REFERENCES

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J. M. Lafferty, "The Hot Cathode Magnetron Ionization Gauge with an Electron Multiplier Detector," Trans. Natl. Symp. Vacuum Tech. 1962, 438 (1962).

2. Mass Spectrometers

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M. A. Florescu, "Reproducible Low Pressures and Their Application to Gauge Calibration," Trans. Natl. Symp. Vacuum Tech. 1961, 504 (1962).

W. H. Hayward and R. L. Jepsen, "A Simple High Vacuum Gauge Calibration System," Trans. Natl. Symp. Vacuum Tech. 1962, 459 (1962).

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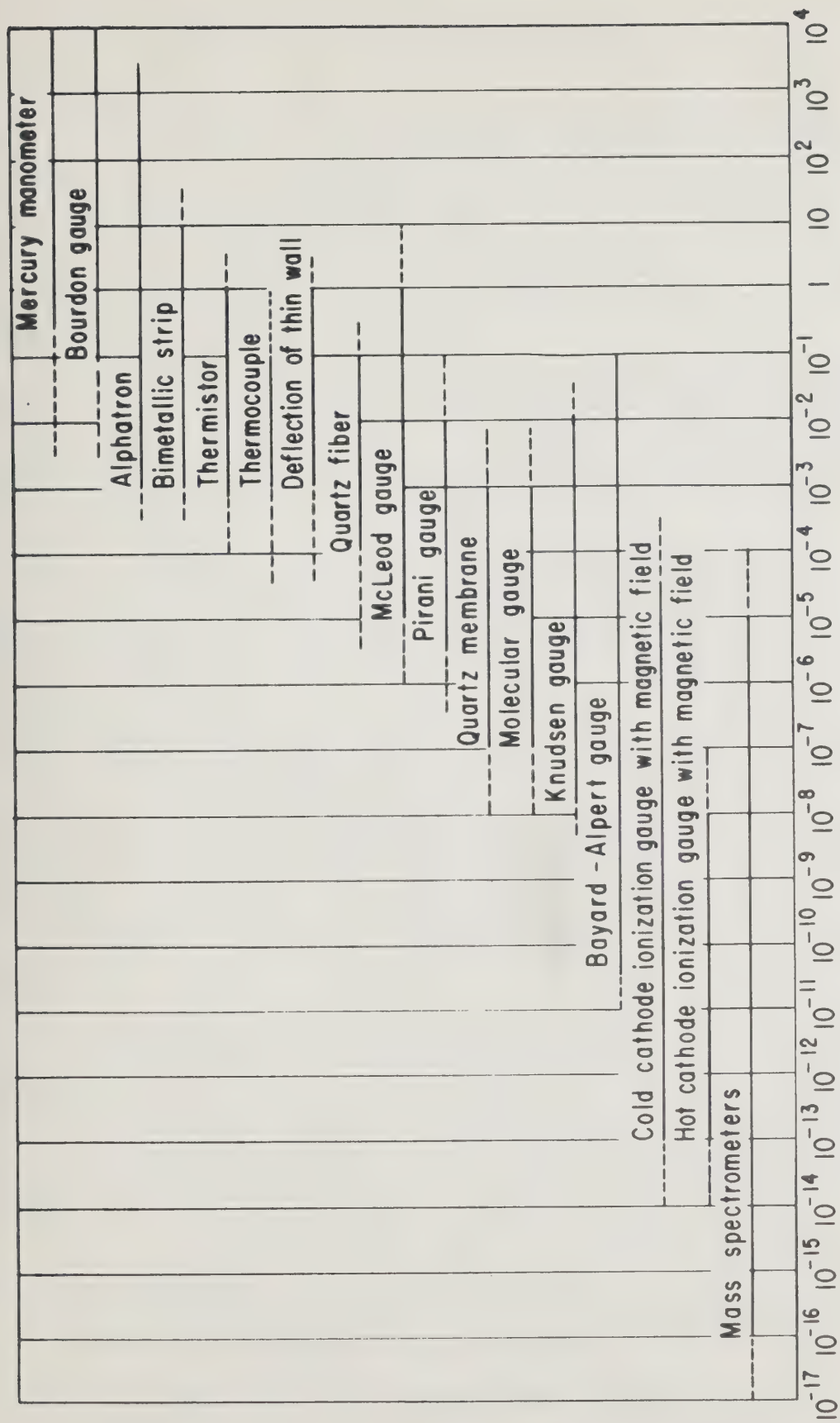
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TABLE XI

The Sensitivity of Ionization Gauges for Various Gases
(from Dushman - 2nd ed., op.cit.)

$$r = \frac{\text{Gauge sensitivity for gas}}{\text{Gauge sensitivity for argon}}$$

<u>Gas</u>	<u>Reynolds</u>	<u>Dushman and Young</u>	<u>Wagener and Johnson</u>	<u>Riddiford</u>	<u>Schulz</u>
He	0.10-0.13	0.13	--	0.24	0.14
Ne	0.12-0.24	0.20	--	--	0.22
Ar	1.00	1.00	1.00	1.00	1.00
Kr	--	1.56	--	--	--
Xe	--	2.29	--	--	--
H ₂	--	0.39	0.44	0.36	0.28
N ₂	0.73-0.81	0.84	0.84	0.94	0.67
O ₂	--	--	0.71	1.07	--
Hg	1.73-2.50	2.89	--	--	--
Dry Air	--	--	--	0.76	--
CO	--	--	0.90	--	--
CO ₂	--	--	1.15	--	--
H ₂ O	--	--	0.75	--	--
SF ₆	--	--	--	--	1.7



PRESSURE IN TORR

Fig. 2 Pressure ranges of various gauges (from S. Dushman, op. cit.).

VIII. VACUUM SEALS

A. INTRODUCTION

Vacuum seals are generally classified as static or motion seals, and may be permanent or demountable. Today, with the increasing use of high-temperature bake-out procedures, seals are often also classified as bakeable or nonbakeable. In general, a nonbakeable seal cannot be used in ultrahigh vacuum systems.

The type of seal used in a system must of course be tailored to the particular problem to be solved. Thus, while grease and rubber gaskets are widely applied in 10^{-6} torr systems, they are to be avoided in 10^{-9} torr systems.

B. STATIC SEALS

Static seals include all nonmovable joints between various parts in a vacuum system whether they be permanent or demountable.

1. Permanent Seals

(a) Glass-to-glass seals are readily made by standard glass blowing techniques, i. e., heating in H_2-O_2 flame, etc. Some care must be taken when joining glasses with different coefficients of expansion. Such seals usually incorporate a number of short lengths of glasses with gradually changing coefficients of expansion so that severe strains do not arise. These are called graded seals.

(b) Ceramic-to-glass seals are generally made by matching the coefficients of expansion.

(c) Metal-to-metal seals are accomplished by soldering, welding, or brazing.

1. Soldering--There are three classifications of soldering: soft-soldering, hard-soldering, and diffusion-soldering. The first two types involve alloys of several metals.

Soft solders usually contain tin and lead (50-50 mixture) and melt around $200^\circ C$. They are useful in joining brass, steel, and other

common metals in nonbaked (10^{-6} torr type) vacuum systems. Other soft solders melt below 400°C .

Hard solders, often called silver solders, contain silver and a variety of other metals. These alloys melt from 400° to about 800°C .

Fluxes are used to remove surface oxides and contaminants before and during soldering.

Diffusion soldering is a relatively low temperature process ($\sim 400^{\circ}\text{C}$) which has been applied to the joining of copper parts. Here a gold wire is placed between two copper parts, the assembly compressed, and heated to about 400°C in H_2 or vacuum. Gold diffuses into the copper, and a strong, vacuum-tight joint results.

2. Welding is defined by the American Welding Society as a metal-joining process in which localized coalescence of a metal is produced by heating to suitable temperatures, with or without the use of a filler metal. The filler metal if used, either has a melting point approximately the same as the base metals or has a melting point below that of the base metals but above 800°F (426.7°C).

Spot Welding or resistance welding is performed by pressing together the parts to be joined and passing a current through them. This technique is widely used to join small parts of a variety of different metals. Table XII lists combinations of metals that can be satisfactorily spot welded.

Heliarc welding or inert atmosphere welding is carried out by resistance heating a joint in an atmosphere of argon or helium. The use of an inert atmosphere eliminates the need for a flux.

Electron beam welding is carried out in a vacuum. The energy loss of an intense beam of electron directed at the joint causes welding to occur. No fluxes are necessary. This method can be used for extreme precision welding.

Metals such as copper, nickel, and Kovar can be cold welded by squeezing them together. This process is usually used to seal tubing and is called pinching.

Ultrasonic Welding is a relatively new technique which makes possible the joining (cold) of a wide variety of materials. A partial listing includes copper, steel, platinum, molybdenum, Inconel, tungsten, tantalum, and aluminum.

3. Brazing is defined by the American Welding Society as a group of welding processes where coalescence is produced by heating to a suitable temperature above 800°F (426.7°C) and by using a nonferrous filler material having a melting point below that of the base metals. The filler material is distributed between the closely fitted surfaces of the joint by capillary attraction.

Brazing of vacuum parts is usually done by heating in a furnace or with rf induction. The atmosphere is either hydrogen or a vacuum and thus eliminates the need for fluxes.

A wide variety of brazing filler materials have been developed. Kohl (op. cit., p. 360 to 364) has listed the composition, melting point application, and supplier for 143 fillers. These are given in Table XIII. Copper, gold, and copper-gold alloys are frequently used in the Research Laboratory.

(d) Glass-to-metal seals--Most vacuum systems contain a number of glass-to-metal seals. These seals are separated into two classes; those in which the coefficients of expansions are matched, and those in which they are unmatched.

A wide range of glass compositions have been developed so that there is usually a glass which can be used to seal directly to a common metal or alloy. The FN-glass/Fernico combination is a typical example. A glass has been developed that will seal directly to massive copper.

In unmatched seals, the stresses are minimized by using ductile metals such as copper (the Housekeeper seal) or by using fine wires or metal foil strips.

Compression Seals have also been developed.

Glasses can also be metalized and soldered to metals.

(e) Ceramic-to-metal seals are made by diffusion, sintered metal powder, or active alloy techniques. Diffusion seals are made by forcing the ceramic part into the metal part at high temperatures. A ceramic part may be metalized by sintering a mixture of Mo (90 per cent) - Mn (10 per cent) powder on it. This surface can be then electroplated with copper and brazed to the metal part. Other metals may be sintered on ceramics. In the active alloy process, the ceramic part is coated with titanium hydride or zirconium hydride and is placed in contact with a thin nickel washer. This assembly is then vacuum fired at $\sim 900^{\circ}\text{C}$.

2. Demountable Seals

A perfect demountable seal is one in which continuous molecular contact between the two mating surfaces takes place. In practice such seals are approached with liquid metal and shear gasket seals. However, there are many applications where greases, waxes, rubber, and plastics may be used as intermediates. These are generally in the 10^{-6} torr systems.

(a) Waxes and greases with relatively low vapor pressures have been used for decades for demountable joints. These may be used to join glass tubes to metal tubes, etc. Standard taper glass joints are usually sealed by greases. Table XIV lists the properties of commercially available waxes, cements, and adhesives. Apiezon greases have fairly low vapor pressures. Dushman (op. cit.) lists their properties. Silicon greases are also used.

These materials cannot be used in bakeable or ultrahigh vacuum systems.

(b) Rubber and plastics are widely used sealing materials in ordinary (10^{-6} torr) vacuum systems.

Ring-shaped gaskets with circular cross section, i.e., O-rings, are widely used for demountable seals. A groove, generally rectangular with beveled edges, whose volume is about 1 per cent greater than that of the O-ring, is cut in one flange. A mating flange with a smooth surface is used to compress the O-ring. The Parker Seal Company (10567 Jefferson Blvd., Culver City, California) has an excellent free catalog (No. 5700) which contains a wealth of O-ring design data.

Gases permeate all polymers to some extent. For the rubbers, Buna N or Neoprene have a lower permeability to gases than do G R-S or natural rubber. Young has found that most rubbers evolve H_2O , CO , N_2 , CO_2 , and a variety of hydrocarbons. Therefore, the use of rubber O-rings is restricted to ordinary (10^{-6} torr) vacuum systems. You cannot heat these rubbers much above $90^\circ C$. Silicone rubber may be used up to $250^\circ C$. It has a higher permeability to air, however. It also has a high coefficient of expansion and a low compressibility.

"Viton," a fluorelastomer, has a low permeability and can be baked to $250^\circ C$. "Teflon" is not too useful as a sealing material because of its tendency to cold flow.

(c) Metal gaskets--Metals have also been used as gasketing materials and sealing agents. Solders and low vapor pressure elements like indium have been used to seal joints. Separation is accomplished by merely reheating the joint.

Annealed gold O-rings compressed between polished metal flanges comprise an excellent ultrahigh vacuum seal. Aluminum, copper, and other materials have also been used.

A partially sheared or compressed flat OFHC copper gasket also provides a good ultrahigh vacuum seal. A variety of flange designs have evolved. These include the knife edge seal, the step seal, the coined gasket seal, and the "Con Flat" seal.

C. MOTION SEALS

1. Greased Joint and Stopcocks

The simplest motion seals are greased joints or stopcocks (useful in ordinary systems only).

2. O-Rings and Washers

O-rings, rubber washers, and spring loaded elastometer washers are widely used as seals around rotating or reciprocating shafts. They do not lend themselves to high-temperature bake out.

3. Metal Bellows

Metal bellows have been used to introduce translational as well as low speed rotational motion into vacuum systems. Levers and gears may be used to amplify the motion. By using low vapor pressure materials, these seals can be used in bakeable ultrahigh vacuum systems.

4. Magnetic Coupling

The transmission of motion by using the coupling of magnetic fields is another widely used technique. The vacuum wall must be made of a nonmagnetic material. Permanent magnets, or electromagnetic induction drives may be used. As we mentioned earlier, Beams has used magnetic levitation and induction to drive a vacuum pump.

5. Low Vapor Pressure Fluid

Motion may also be introduced in ultrahigh vacuum systems by using a low vapor pressure liquid to form a seal around a shaft going through the vacuum wall. Liquid nitrogen trapped mercury has been used. A eutectic mixture of gallium, indium, and tin has also been used with good results. This material melts at 10.7 °C and has a vapor pressure of less than 10^{-8} torr at 500°C.

D. REFERENCES

Roberts and Vanderslice, op. cit.

Kohl, op. cit.

Pirani and Yarwood, op. cit.

TABLE XII

Spot Welding of Various Metal Combinations
(adapted from M. von Ardenne, op. cit.)

2 1		Al	Ag	Cu	Cu Be	Cu Ni	Ni Cu	Fe Cr Ni	Ni Cr	Fe Ni	Fe Ni Co	Fe Ni	Fe Pt	Mo	Ta	W
W		4	4	4	3	3		2, 5			3, 4	2	3	3, 5, 6	3, 5	3, 5
Ta		3	3, 4	3, 5	1	2		1			2, 3	2	3	3, 5, 6	3, 5	
Mo		4	4	4	3	3	2	2		2	3	2	3	3, 5, 6		
Pt		3, 4	3, 4	2	1	2	1	1	1	1	2	1	1			
Fe		3	3	2, 3	3	2	2	1	2		3	1	1			
Fe Cr (70/30)		3, 4		4						3		2	2			
Ni		3, 4	3	3	1	2	2	1	2		2	1				
Kovar Fe Ni Co		3, 4	4	3, 4	3	3			2		3					
Invar Fe Ni		4					2		2			2				
Ni Cr (80/20)		4			1	2	2	1	2							
V 2 A Fe Cr Ni		4	3	3, 4	1	2		1								
Monel Ni Cu		4					2									
Constantan Cu Ni		2	3, 4		2	2										
Cu Be (97.5/2.5)		3	3	2, 3	1											
Cu		4	4	3												
Ag		4	3													
Al		3														

EXPLANATION

1. Very good weld

2. Good weld

3. Adequate weld

4. Poor weld or no weld

5. Weld under a protective fluid

6. Weld with an intermediate layer of tantalum foil 0.002" to 0.004" thick

EXPLANATION

1. Very good weld
2. Good weld
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6. Weld with an intermediate layer of tantalum foil 0.002" to 0.004" thick

TABLE XIII
Brazing Filler Metals for Electron Tubes*

No.	Liquid, Deg. C	Solid, Deg. C	Composition in Weight Percent ¹	Liquid, Deg. F	Solid, Deg. F	Notes	Alloy Designations and Suppliers ²	Applications and Comments ³
1	3180	3180	Rhenium	5756	5756		CBC; (GPD)	W
2	2996	2996	Tantalum	5425	5425	4B	FMC	W
3	2468	2468	Columbium (Niobium)	4474	4474	4B	FMC	Mo, W
4	2480	2480	Tungsten Carbide (W,C)	4496	4496		CC	Mo, W, W,C
5	2500	2500	Ruthenium	4532	4532		BPD; SCC; (GPD); (HH)	Mo, W
6	2450	2450	Iridium	4442	4442		BPD; SCC; (GPD); (HH)	Mo, W
7	2150	2120	Silicon-Molybdenum 10 90	3902	3848		TMC; VMC	
8	2080	2000	Dimolybdenumboride	3776	3632		BC	Mo, W
9	1990	1950	Iridium Platinum 40 60	3614	3542		BPD; SCC; (GPD)	
10	1966	1966	Rhodium	3574	3574		BPD; SCC; (GPD); (HH)	Mo, W
11	1950	1935	Rhodium Platinum 40 60	3542	3515		BPD; SCC; (GPD)	Mo, W
12	1900	1900	Ruthenium Molybdenum 20 80	3452	3452		BPD; SCC	Mo, W
13	1852	1852	Zirconium	3366	3366	4B	CC; FMC	Mo, W
14	1769	1769	Platinum	3216	3216		APW; BPD; HH Platinum VTG ; INCO; SCC; WGP; (GPD)	Mo; W
15	1695	1645	Gold-Palladium-Platinum 5 20 Bal.	3083	2993		HH Premabraz 205 VTG	Mo; W
16	1660	1660	Titanium	3320	3320		LFA et al	Ceramic seals
17	1552	1552	Palladium	2826	2826	4B	APW; BPD; HH Palladium VTG ; INCO; WGP; (GPD)	Mo; W
18	1445	1445	Nickel-Iron 36 64	2651	2633		ASC Ascovar 36 ; DHC Nilvar ; Inco Invar ; SEP	(NAHg)
19	1453	1453	Nickel	2647	2647		DHC; INCO; WBD	Mo; W
20	1440	1427	Palladium-Gold 35 65	2624	2601		ASC Ascobraz 65AC ; JMN; (HH); (GPD); (WGP)	
21	1410	1380	Palladium-Gold 25 75	2570	2516		HH Premabraz 201 VTG	Mo; W
22	1410	1210	Platinum-Gold 25 75	2570	2210		ASC Ascovar 75AD ; JMN; (GPD); (HH); (WGP)	Mo; W
23	1330	1330	Molybdenum-Cobalt 37 63	2426	2426			Mo; W
24	1320	1320	Molybdenum-Nickel 46.5 53.5	2408	2408			Mo; W; Ni; (NM)
25	1320	1290	Palladium-Nickel 30 70	2408	2354		ASC Ascobraz 70EC ; (BPD); (GPD); (HH)	SS
26	1305	1260	Palladium-Gold 13 87	2381	2300		HH Premabraz 210 VTG	Mo; W
27	1300	1230	Nickel-Copper 45 55	2372	2246		ASC Ascobraz 55FE ; DHC Advance ; WBD Cupron ; Constantan, Eureka	Mo; W; (NM)
28	~1260	>1232	Chrome-Nickel-Palladium 10 36 Bal.	2300	>2250		HH Premabraz 101 ; (GPD)	
29	1250	1200	Platinum-Copper 40 60	2282	2192		ASC Ascobraz 60FD ; WGP Cuplat ; (GPD) (HH)	
30	1240	1190	Palladium-Gold 8 92	2264	2174		ASC Ascobraz 92AC ; WGP Paloro ; (GPD); (HH)	Mo; W; SS
31	1240	1170	Iron-Nickel-Copper 0.6 30 Bal.	2264	2138		ABC Cupro Nickel 30 702 ; ASC Ascobraz 70FE	Mo; W; (NM), Watch for Zn
32	1238	1238	Nickel-Palladium 40 60	2260	2260		APW APW 129 ; BPD Alloy No. 940 ; (GPD); (HH)	SS; Inconel
33	1232	1149	Manganese-Palladium-Silver 3 33 Bal.	2250	2100		APW APW 441 ; BPD Alloy No. 1170 ; (GPD)	SS; Inconel
34	1220	1220	Cobalt Palladium 35 65	2228	2228		ASC Ascobraz 65CG ; WGP Palco ; (GPD); (HH)	Mo; W; SS; Inconel
35	1205	1150	Nickel-Copper 25 75	2201	2102		ABC Cupro Nickel 25 705 ; ASC Ascobraz 75FE ; Coin Nickel	Mo; W; (NM)
36	1160	1070	Palladium-Silver 20 80	2120	1958		(GPD); (HH); (WGP)	
37	1160	995	Platinum-Silver 27 73	2120	1823		ASC Ascobraz 73BD ; (GPD); (HH); (WGP)	Mo; W
38	1160	971	Carbon-Boron-Silicon-Iron- 0.45 max 2 2.5 2.5 Chromium-Nickel 10 Bal.	2120	1780	4A, B	APW; WCC Microbraz 160	SS; Inconel

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Revised 1959 for "MATERIALS and TECHNIQUES for ELECTRON TUBES," by W. H. Kohl, Reinhold Publishing Corporation, New York, N. Y.
Separately printed copies of this table are available as wall charts or file copies from the author.
Manufacturers of Brazing Materials have generously cooperated in the preparation of this table; their help is gratefully acknowledged. The data published in this table must, however, not be construed as committing the respective manufacturers in any way or form.

Table XIII (continued)

No.	Liquid, Deg. C	Solid, Deg. C	Composition in Weight Percent ¹	Liquid, Deg. F	Solid, Deg. F	Notes	Alloy Designations and Suppliers ²	Applications and Comments ³
39	1150	1100	Iron-Nickel-Copper 1.3 10 Bal.	2102	2012		Cupronickel 10g	(NM); Watch for Zn
40	1135	1080	Iron-Silicon-Chromium-Nickel 3 10 19 Bal.	2075	1975	4A, B, C	CM Alloy No. 60	SS; Inconel
41	1135	1080	Carbon-Silicon-Chromium-Nickel 0.15 max 10 19 Bal.	2075	1975		APW; WCC Microbraz 30	SS; Inconel
42	1121	1071	Manganese-Palladium-Silver 5 20 Bal.	2050	1960		APW APW 440; BPD Alloy No. 1795; (GPD)	SS; Inconel
43	1105	977	Carbon-Boron-Silicon-Iron 0.55 2.5 3.25 3.75 Chromium-Tungsten-Nickel 11.5 16 Bal.	2020	1790	4A, B	APW; WCC Microbraz 170	Mo; W; SS; Inconel
44	1105		Manganese-Nickel-Palladium-Copper 10 15 20 Bal.	2020			BPD Alloy No. 1804; (GPD)	
45	1094	971	Carbon-Boron-Silicon-Iron 0.15 max 3 3.5 3.5 Chromium-Nickel 11.5 Bal.	2000	1780	4A, B	APW; WCC WG Microbraz	SS; Inconel
46	1090		Manganese-Nickel-Palladium-Copper 15 20 30 Bal.	1994			BPD Alloy No. 1803; (GPD)	SS
47	1090	1080	Palladium-Copper 18 82	1994	1976		BPD Alloy No. 1800; (GPD); (HH)	
48	1083	1083	Copper	1981	1981	[B Cu]	ABC OFHC Copper 120; ASC Ascobraz 0FHC; EWA EutecRod 184	Fe; Kovar; Monel
49	1083	1083	Nickel-Copper-Tungsten 3 35 Bal.	1981	1981		MWP Runnot C	Fe; Kovar; Monel; Contains W powder
50	1083	1083	Silicon-Copper 0.3 Bal.	1981	1981	Cu Base H (SAE)	ABC, RCB Silicon Copper 107; ASC Ascobraz 99FH	For Fe-Ni alloys
51	1077	971	Carbon-Boron-Silicon-Iron 0.15 max 3.5 4.5 4.5 Chromium-Nickel 13.5 Bal.	1970	1780	AMS 4776 4A, B	APW; WCC LC Microbraz	Inconel; SS
52	1075	965	Nickel-Gold 35 65	1967	1769	5	HH Premabraz 131 VTG; (GPD); (WGP)	
53	1070	1070	Tin-Platinum 29 71	1958	1958		ASC Ascobraz 70DJ; (GPD)	
54	1065	1002	Palladium-Silver 10 90	1950	1835	5	APW Alloy No. 431; ASC Ascobraz 90BC; HH Premabraz 901 VTG; (GPD); (WGP)	Mo; Ni; SS; W
55	1065	974	Chromium-Nickel-Gold 6 22 Bal.	1950	1785		APW Alloy No. 265; HH Premabraz 128; (WGP)	
56	1065	954	Boron-Silicon-Chromium 3 max 5 max 20 max Manganese-Nickel 30 max 60-85	1950	1750		SAC Solobraz NXI	SS
57	1063	1063	Gold	1945	1945		APW Alloy No. 200; ASC Ascobraz 99, 99A; HH Fine Gold VTG; WGP 24 Karat Gold; (GPD)	Diffusion seals; Cu; Mo
58	1060	1000	Silver-Copper 5 95	1940	1832	5	ASC Ascobraz 95FB; HH Braze 052 VTG; (GPD); (WGP)	Cu
59	1055	1055	Carbon-Boron-Chromium-Nickel 0.15 max 3.5 15 Bal.	1930	1930	4A, B	APW; WCC Microbraz 150	Inconel; SS
60	(1055)	1041	Boron-Silicon-Nickel 1.9 3.5 Bal.	(1930)	1905	7	CM Alloy No. 50; HH Handy Hi-Temp 93	Inconel; SS
61	1050		Manganese-Palladium-Silver 5 20 Bal.	1922			BPD No. 1168; (GPD)	
62	1050	1030	Nickel-Manganese 30 70	1922	1886		HH Handy Hi-Temp 30	SS
63	1038	1027	Carbon-Boron-Silicon-Nickel 0.15 max 3 4.5 Bal.	1900	1800	4A, B	APW; WCC Microbraz 130	Inconel; SS
64	1038	977	Carbon-Boron-Iron-Silicon 0.8 3.5 4.5 4.5 Chromium-Nickel 13.5 Bal.	1900	1790		APW; WCC Microbraz 120	Differs in mesh size from Standard
65	1038	971	Carbon-Boron-Iron-Silicon 0.60 3.85 4 4.5 Chromium-Nickel 16.5 Bal.	1900	1780	[B Ni Cr] AMS-4775 4A, B	CM No. 56; CSC Rexweld 64; EWA EutecBor 9; WCC Standard Microbraz	Inconel; SS
66	1035	1015	Gold-Copper 30 70	1895	1859	5	ACS Ascobraz 70FA; HH Premabraz 404 VTG; (GPD); (WGP)	Cu; Fe; Kovar; Ni
67	1032	1010	Carbon-Silicon-Manganese-Nickel 0.15 max 8 17 Bal.	1890	1850	4A, B, C	APW; WCC Microbraz 60	Inconel; SS
68	1030	975	Nickel-Gold-Copper 3 35 Bal.	1886	1787		HH Premabraz 129 VTG	Cu; Kovar; Mo; Monel; Ni; W
69	1025	970	Silicon-Copper 3 97	1877	1778		EWA EutecRod 182; RCB	Cu
70	1021	1005	Boron-Nickel-Cobalt-Manganese 1 16 16 Bal.	1870	1840		CM Alloy No. 62	SS

Table XIII (continued)

No.	Liquid, Deg. C	Solid, Deg. C	Composition in Weight Percent ¹	Liquid, Deg. F	Solid, Deg. F	Notes	Alloy Designations and Suppliers ²	Applications and Comments ³
71	1020	1000	Gold-Copper 35 65	1868	1832	5, 8	APW Alloy No. 260; ASC Ascobraz 65FA; HH Premabraz 406 VTG; WGP Wesgo; (GPD)	Cu; Fe; Kovar; Ni
72	1025	990	Nickel-Gold-Copper 3 35 Bal.	1877	1814	5, 8	APW Alloy No. 243; ASC Ascobraz 62FAE; WGP Nicoro; (GPD)	Cu; Inconel; Kovar; Mo; Ni; Steel; W
73	1019	950	Manganese-Silicon-Copper 1.1 3.1 Bal.	1866	1742		ABC Everdur 1010	
74	1018	1018	Nickel-Manganese 40 60	1864	1864			SS
75	1015	990	Gold-Copper 37.5 62.5	1859	1814	[BCuAu-1] 5; 9 Karat red gold	APW Alloy No. 242; ASC Ascobraz 62FA; HH Premabraz 401 VTG; WGP; (GPD)	Cu; Fe; Kovar; Ni
76	1015	970	Indium-Gold-Copper 3 20 Bal.	1859	1778		ASC Ascobraz 77FAK; WGP Incuro 20	Cu; Kovar; Ni
77	1010	985	Gold-Copper 40 60	1850	1805	8	ASC Ascobraz 60FA; WGP Wesgo; (HH); (GPD)	Cu; Fe; Kovar; Ni
78	1010	970	Palladium-Silver 5 95	1850	1778		BPD Alloy No. 868; (HH)	
79	(1005)	996	Boron-Silicon-Chromium-Nickel-Iron 3.50 5 16 72.50 Bal.	(1840)	1825	7	HH Handy Hi-Temp 72	Inconel; SS
80	999	971	Carbon-Iron-Boron-Silicon 0.15 max 2.5 3 4.5 Chromium-Nickel 6.5 Bal.	1830	1780	AMS 4777 4A, B	APW; WCC LM Microbraz	Inconel; SS
81	(996)	979	Boron-Silicon-Chromium-Nickel-Iron 2.90 4.50 7.00 82 Bal.	(1825)	1795	7	CM Alloy No. 53; HH Handy Hi-Temp 82	SS
82	(993)	979	Boron-Silicon-Nickel-Iron 2.90 4.50 91.25 Bal.	(1820)	1795	7	CM Alloy No. 52; HH Handy Hi-Temp 91	Cu; SS
83	993	979	Titanium-Boron-Silicon-Iron 0.75 3 4.5 Bal.	1820	1795		CM Alloy No. 59	
84	990	965	Copper-Gold 6 94	1814	1769		APW Alloy No. 259; ASC Ascobraz 94AF; (HH); (GPD); (WGP)	
85	985	664	Silver-Tin-Copper 7 8 Bal.	1805	1225	5	APW D-275; ASC Ascobraz 85FJB; GSR GB07; HH Braze 071 VTG; UWS Sil-7T; WEC Co-Silver 7T; (GPD)	
86	975	950	Copper-Gold 50 50	1787	1742	5, 8	APW Alloy No. 241; ASC Ascobraz 50AF; HH Premabraz 402 VTG; WGP Wesgo	Cu; Kovar; Ni
87	971	960	Manganese-Silver 15 85	1780	1760	[B ₂ AgMn]	APW Silvaloy 850; ASC Ascobraz 85BL; ARS Aircosil P; EWA EutekRod 1807; GSR GB No. 85; HH Braze 852; UWS Sil 85 M; WEC Co-Silver 85; (GPD)	Inconel; SS
88	963	924	Silver-Gold-Copper 2.8 41.7 Bal.	1765	1695	5	ASC Ascobraz 55FAB; HH Premabraz 031 VTG; (GPD)	Cu; Kovar
89	962		Nickel-Silver-Tungsten 3 35 Bal.		1764		MWP Runnet S	Contains W powder
90	961	961	Manganese-Silver 4 96	1762	1762		ASC Ascobraz 96BL; (HH); (GPD)	
91	960.5	960.5	Silver	1761	1761		APW; ASC Ascobraz 99.9B; HH Fine Silver VTG; WGP; (GPD)	Very ductile
92	950	950	Nickel-Gold 18 82	1742	1742	5 19.8 Karat White Gold	APW Alloy No. 255; ASC Ascobraz 82AE; HH Premabraz 130 VTG; WGP Nicoro; (GPD)	Cu; Inconel; Kovar; Mo; Ni; W; SS
93	950	779	Silver-Copper 30 70	1742	1434		ASC Ascobraz 70FB; (GPD); (HH); (WGP)	
94	950		Palladium-Copper-Silver 10 22.5 Bal.	1742			BPD Alloy No. 1802; (GPD); (HH)	
95	950	901	Copper-Palladium-Silver 21 25 Bal.	1742	1654		BPD Alloy No. 1799; (GPD); (HH)	
96	942	942	Nickel-Titanium 28.5 71.5	1728	1728		LFA Ni-clad-Ti	Ceramic seals; (NM)
97	921	905	Silver-Copper-Gold 2.1 39.6 Bal.	1690	1660	5	ASC Ascobraz 59AFB; HH Premabraz 032 VTG; (GPD); (WGP)	Ferrous and nonferrous alloys
98	913	871	Copper-Cobalt-Phosphorus 5 7.5 11 Nickel-Iron 42 Bal.	1675	1600		CM Alloy No. 57	
99	910	900	Nickel-Copper-Gold 3.0 15.5 Bal.	1670	1652		ASC Ascobraz 82AFE; WGP Nicoro 80; HH Premabraz 409 VTG; (GPD)	Cu; Kovar; Mo; Ni; W; Steel
100	910	779	Silver-Copper 40 60	1670	1434	5	ASC Ascobraz 60FB; HH Braze 401 VTG; (GPD); (WGP); (German BTL)	Ferrous and nonferrous alloys

Table XIII (continued)

No.	Liquid, Deg. C	Solid, Deg. C	Composition in Weight Percent ¹	Liquid, Deg. F	Solid, Deg. F	Notes	Alloy Designations and Suppliers ²	Applications and Comments ³
101	900	860	Indium-Copper-Gold 3.0 37 Bal.	1652	1580		ASC Ascobraz 60AFK ; WGP Incuro 60 ; (GPD)	Cu; Fe; Kovar; Ni
102	900	850	Palladium-Copper-Silver 15 20 Bal.	1652	1562		BPD Alloy No. 1798 ; (GPD); (HH)	
103	900	714	Phosphorus-Copper 5 95	1653	1317	[BCuP-1] CuBase B (SAE)	ARS, WEC Phos Copper Strip ; BSR Belmont BCuP 1	Ag; Cu; Mo; W; Not for Fe or Ni alloys
104	898	879	Palladium-Copper-Silver 20 28 Bal.	1648	1614		BPD Alloy No. 1801 ; (GPD); (HH)	
105	896	885	Silver-Copper-Gold 5 20 Bal.	1645	1625	5	APW Alloy No. 261 ; ASC Ascobraz 75AFB ; HH Premabraz 050 VTG ; WGP Silcoro 75 ; (GPD)	
106	888	888	Carbon-Phosphorus-Chromium-Nickel 0.15 max 10 13 Bal.	1630	1630	4A, B, C	APW, WCC Microbraz 50	Inconel; SS
107	890	810	Copper-Silver 7.5 92.5	1634	1490	5	ASC Ascobraz 92BF ; HH Sterling Silver VTG ; (GPD); (WGP)	
108	890	780	Lithium-Copper-Silver 0.2 7.3 Bal.	1635	1435		APW, ARS AE 100 ; ASC Ascobraz 92BFN ; HH Lithobraz 925 ; (GPD)	Inconel; SS; Extremely fluid
109	889	889	Copper-Gold 20 80	1632	1632	[BCuAu-2] 5; 19.2K red gold	APW Alloy No. 238 ; ASC Ascobraz 80AF ; HH Premabraz 403 VTG ; JMN .800 Fine ; (GPD)	
110	885	779	Nickel-Copper-Silver 5 32.5 Bal.	1625	1435		APW Silvaloy T 50 ; (GPD); (HH)	Inconel; SS
111		800	Manganese-Silver-Copper 10 40 Bal.		1472		(GPD); (HH); (German Kusiman)	Ag; Fe; Steel
112	877	877	Carbon-Phosphorus-Nickel 0.15 max 11 Bal.	1610	1610	4A-D	APW, WCC Microbraz 10 ; INCO Niphos (German)	Cu; Fe; Inconel; Kovar; Mo; Ni; W; SS
113	875	779	Copper-Silver 50 50	1607	1434	5	ASC Ascobraz 50BF ; HH Braz 502 VTG ; (GPD); (WGP)	
114	870	779	Copper-Silver 10 90	1598	1434	5	ASC Ascobraz 90BF ; HH Coin Silver VTG ; (GPD); (WGP)	SS
115	852	824	Palladium-Copper-Silver 10 31.5 Bal.	1566	1515		BPD Alloy No. 1797 ; (GPD); (HH)	
116	849	752	Nickel-Manganese-Copper-Silver 2 5 28 Bal.	1560	1385		ASC Ascobraz 65BF LE ; GSR 65 Mn ; HH Braz 655 ; (GPD)	Stellites, carbides, and refractory metals containing W
117	845	835	Silver-Copper-Gold 20 20 Bal.	1553	1535	5	ASC Ascobraz 60AFB ; HH Premabraz 408 VTG ; WGP Silcoro 60 ; (GPD)	Cu; Fe; Ni; Very short melting range
118	843	815	Copper-Silver-Gold 17.7 24 Bal.	1550	1500		ASC Ascobraz 58ABF ; (HH); (WGP)	Cu; Fe; Ni
119	830	779	Nickel-Copper-Silver 2 21 Bal.	1525	1435		APW Silvaloy T 52 ; (GPD); (HH)	Inconel; SS
120	824	794	Copper-Silver-Gold 23.5 27.5 Bal.	1515	1460	12 Karat Gold	ASC Ascobraz 49ABF ; (GPD); (HH); (WGP)	Cu; Fe; Ni
121	827	805	Copper-Silver-Gold 23.5 23.5 Bal.	1520	1480		JMN No. 5087 ; (GPD); (HH); (WGP)	Cu; Fe; Ni
122	821	794	Copper-Silver-Gold 20.5 29.5 Bal.	1510	1460	5	ASC Ascobraz 50 ABF ; HH Premabraz 202 VTG ; (GPD); (WGP)	Cu; Fe; Ni
123	815	641	Phosphorus-Silver-Copper 5 15 Bal.	1500	1185	[BCuP-5] 6	APW Silvaloy 15 ; ARS Aircosil 15 ; ASW S-115 ; EWA EutecRod 1803 ; GSR 15 ; HH Sil-Fos ; UWS Phoson 15 ; WEC Phos Silver 15 M	Not for Fe or Ni alloys. Wide melting range.
124	805	644	Silver-Phosphorus-Copper 5 6.25 Bal.	1480	1190	[BCuP-3] 6	APW Silvaloy 5 ; ARS Aircosil 5 ; ASC Ascobraz FOS 5 ; HH Sil-Fos 5 ; UWS Phoson 6 ; WEC Phos-Silver 6M	Ag; Cu; Mo; W; Not for Fe or Ni alloys
125	810	807	Palladium-Copper-Silver 5 26.6 Bal.	1490	1485		BPD Alloy No. 1796 ; (GPD); (HH)	
126	802	719	Nickel-Tin-Copper-Silver 2.5 6 28.5 Bal.	1475	1325	5	ASC Ascobraz 63 BFJE ; HH Braz 630 VTG ; (GPD)	Inconel; SS 430
127	795	780	Nickel-Copper-Silver 0.75 28.1 Bal.	1463	1436	5	ASC Ascobraz 71BFE ; HH Braz 720 VTG ; WGP Nicuil 3 ; (GPD)	Inconel; Mo; SS; W; Better wetting than Cu/Ag
128	788	640	Silver-Phosphorus-Copper 2 7 Bal.	1450	1185		ARS Phos-Silver 2 ; ASW 23 ; GBS 02	For nonferrous metals and alloys
129	780	660	Indium-Copper-Silver 10 27 Bal.	1436	1220	5, 8	ASC Ascobraz 63 BFK ; HH Premabraz 630 VTG ; WGP Incusil 10 ; (GPD)	
130	779	779	Copper-Silver (Eutectic) 28 72	1435	1435	[BAg-8]	APW Silvaloy 301 ; ARS Aircosil M ; ASC Ascobraz 72BF ; EWA EutecRod 1806 ; GPD ML ; GSR 72 ; HH Braz BT VTG ; SC Nu Braz ; UWS Sil-72 ; WEC Co-Silver 72-28 ; WGP Cusil-Decarbonized ; (GPD)	Cu; Inconel; Kovar; SS
131	770	714	Phosphorus-Copper 7 93	1418	1317	[BCuP-2] 6	ASW 21 ; ARS, WEC Phos Copper Rod ; BSR Belmont BCuP-2 ; CLA Lo-Melt Copper ; EWA EutecRod 800 ; UWS Phoson 0	Ag; Cu; Mo; W; Very free flowing; Not for Fe or Ni alloys

Table XIII (continued)

	Liquid, Deg. C	Solid, Deg. C	Composition in Weight Percent ¹	Liquid, Deg. F	Solid, Deg. F	Notes	Alloy Designations and Suppliers ²	Applications and Comments ³
132	760	743	Tin-Copper-Silver 5 27 Bal.	1400	1370		ASC Ascobraz 68 BFJ ; GPD SI-1; (HH)	
133	730	604	Manganese-Tin-Copper-Silver 3 7 32.7 Bal.	1345	1120		ASC Ascobraz 57BFJL ; EWA EutecRod 1602 ; HH Braze 580; (GPD)	Chrome carbides
134	721	640	Silver-Phosphorus-Copper 5.5 7.25 Bal.	1330	1190	[BCuP-4] 6	ARS Phos-Silver 6 ; GSR 06 ; WEC Phos Silver	Ag; Cu; Mo; W; Not for Fe or Ni alloys
135	718	602	Tin-Copper-Silver 10 30 Bal.	1325	1115	5	APW Silvaloy 60 ; ASC Ascobraz 60BFJ ; GSR 160 ; HH Braze 603 VTG ; UWS Si-60T ; WEC Co-Silver 60T	
136	705	635	Indium-Copper-Silver 13 27 Bal.	1300	1175		ASC Ascobraz 60BFK ; GSR 260 ; (GPD); (HH)	
137	685	630	Indium-Copper-Silver 15 24 Bal.	1265	1166	5	ASC Ascobraz 61BFK ; HH Premabraz 615 VTG ; WGP Incusil 15 ; (GPD)	
138	485	473	Indium-Gold 20 80	905	883		ASC Ascobraz 80AK ; ICA 19.2K	Cu; Fe; Ni; Hard, brittle joints
193	425	425	Indium-Gold 25 75	797	797		ASC Ascobraz 75AK ; ICA 18K	Hard, brittle joints
140	232	232	Tin	450	450			Rarely used, poor wetting
141	230	166	Silver-Indium 10 90	446	331		ICA Indalloy No. 3	
142	157	157	Indium	315	315		ICA Indalloy No. 4	
143	117	117	Indium-Tin 50 50	225	225		ICA Indalloy No. 1	

NOTES

- 1—Alloy constituents are given in this sequence: the smallest additive first, others in increasing order, with the bulk constituent last, as balance.
- 2—Code letters signify suppliers and are alphabetically listed below. Names following code letters and in bold face are registered trademarks of the supplier. Code letters in parentheses signify that the alloy is not a stock item but can be custom-made. Omission of a supplier does not imply that the quality of his products is inferior.
- 3—The chemical symbols for metals (Mo = molybdenum, W = tungsten, W₂C = tungsten carbide, Ni = nickel, Fe = iron, Cu = copper, Ag = silver) and the names of alloys, or abbreviations (SS = stainless steel), suggest parent metals which may be joined by the filler metal in question. (NM) = nonmagnetic; (NAHg) = not attacked by mercury.
- 4—Brazing operations for electron devices must be performed in inert or reducing atmospheres, or in vacuum: a—Pure dry hydrogen or inert gases, b—Vacuum, c—Dissociated ammonia (—60°F dew point or better), d—Exothermic; rich, unpurified 6:1 air to gas ratio, or purified and dried.
- 5—Handy & Harman alloys marked "VTG" are produced as "Vacuum Tube Grade" with specially controlled, low impurity content, if so ordered. Items

not marked VTG are not available from HH at this controlled level but as commercial alloys only. It might be well to emphasize Vacuum Tube Application when ordering alloys from other suppliers and to watch impurity content in all cases.

- 6—The liquidus temperatures of the Ag-Cu-P alloys Numbers 123 and 124 are 1480 1500°F; their working temperatures are near 1300°F.

- 7—The temperatures listed as liquidus temperatures for B-Si alloys No.'s 60, 81, and 82 are working temperatures rather than liquidus temperatures.

- 8—Alloys #68 and #72 are a duplication, and different values are given for liquidus and solidus. Entry #68 presents data recently released by Handy & Harman, while #72 is close to values published by Western Gold & Platinum Company. Similarly, the HH values for alloys #71, 75, 77, 86, 129 are higher than those given by WGP who believe on the basis of their own extensive tests, substantiated by others, that their data are correct. The author of this chart does not intend to discriminate against these claims. Similar discrepancies may exist in other cases. Double entries contained in the original manuscript were eliminated to avoid confusion.

SUPPLIERS

ARS Air Reduction Sales Company 150 East 42nd Street New York 17, N. Y.	CC The Carborundum Company P. O. Box 337 Niagara Falls, N. Y.	GSR Goldsmith Bros. Smelting & Refining Co. 1300 W. 59th Street Chicago 36, Ill.	SCC Sigmund Cohn Corporation 121 S. Columbus Avenue Mt. Vernon, N. Y.
ASW All-State Welding Alloys Company, Inc. 249 55 Ferris Avenue White Plains, N. Y.	CBC Chase Brass & Copper Company 236 Grand Street Waterbury 20, Conn.	HH Handy & Harman 82 Fulton Street New York 38, N. Y.	SAC Solar Aircraft Company 2200 Pacific Highway San Diego 12, Calif.
ABC American Brass Company 414 Meadow Street Waterbury 20, Conn.	CM Coast Metals, Inc. 199 Rednick Avenue Little Ferry, N. J.	ICA The Indium Corporation of America 1676 Lincoln Avenue Utica 4, N. Y.	SEP Sylvania Electric Products, Inc. Chemical and Metallurgical Division Towanda, Pa.
APW American Platinum & Silver Division Engelhard Industries, Inc. 231 New Jersey Railroad Avenue Newark 5, N. J.	CSC Crucible Steel Company of America Oliver Bldg., Mellon Square Pittsburgh 22, Pa.	INCO The International Nickel Co., Inc. 67 Wall Street New York 5, N. Y.	TMC Temescal Metallurgical Corporation 1201 S. 47th Street Richmond, Calif.
ASC American Silver Company, Inc. 36 07 Prince Street Flushing 54, N. Y.	DHC Driver-Harris Company 201 Middlesex Street Harrison, N. J.	JMC Johnson, Matthey & Company, Inc. 608 5th Avenue New York, N. Y.	UWS United Wire & Supply Corporation Providence 1, R. I.
BPD Baker Platinum Division Engelhard Industries, Inc. 113 Astor Street Newark 5, N. J.	EWA Eutectic Welding Alloys Corporation 40 40 172nd St. Flushing 58, N. Y.	LFA Little Falls Alloys, Inc. 189 Caldwell Ave. Paterson 1, N. J.	VMC Vacuum Metals Corporation Div. of Crucible Steel Co. of America P. O. Box 977 Syracuse 1, N. Y.
BSR Belmont Smelting & Refining Works, Inc. 330 Belmont Avenue Brooklyn 7, N. Y.	FMC Fansteel Metallurgical Corporation 2200 Sheridan Road North Chicago, Ill.	MWP Metallwerk Plansee Reutte, Tirol Austria	WCC Wall Colmonoy Corporation 19345 John R Street Detroit 3, Mich.
BC The Borolite Corporation Box 337 Niagara Falls, N. Y.	FMC Foote Mineral Company 18 W. Chelton Avenue Philadelphia 44, Pa.	JMN J. M. Ney Company P. O. Box 990 Hartford 1, Conn.	WGP Western Gold & Platinum Company 525 Harbor Boulevard Belmont, Calif.
CLA Canadian Liquid Air Company Limited 1111 Beaver Hall Hill Montreal, P. Q.	GPD General Plate Division Metals and Controls Division Texas Instruments Incorporated 34 Forest Street Attleboro, Mass.	RCB Revere Copper and Brass Incorporated 230 Park Avenue New York 17, N. Y.	WEC Westinghouse Electric Corporation P. O. Box 868 Pittsburgh 30, Pa.
			WBD Wilbur B. Driver Company 1875 McCarter Highway Newark 4, N. J.

TABLE XIV

Waxes, Cements, and Adhesives
(from Pirani and Yarwood, *op. cit.*)

Material	Softening temp. °C	Vapour pressure torr	Remarks
Apiezon 'Q' compound	20 to 30	Order of 10^{-4} at 20° C	Plasticine-like mixture of graphite and paraffin oil distillation residues. Can be pressed with fingers round joint to make temporary seal
Apiezon W wax Apiezon W40 wax Apiezon W100 wax	60 30 50	10^{-6} at 20° C 10^{-3} at 180° C	W40 used where temperature of parts must be kept low. Black waxes available in sticks. Soluble in xylene. W40 and W100 less brittle than W
Araldite	120	2×10^{-7} at 20° C	Curing process necessary. Available in sticks or powder form. Cold-setting Araldite also available.
Edwards W.E. wax 3 Edwards W.E. wax 6	80 90	10^{-6} at 20° C 10^{-6} at 20° C	Shellac-based brown wax soluble in alcohol (unlike Apiezon W and Picein). Fairly insoluble in benzene, toluene and other aromatic hydrocarbons. Available in sticks. Product of Edwards High Vacuum Ltd. W.E. 6 has been much used for sealing strain-gauge wires
Khotinsky cement	50	10^{-3} at 20° C	Mixture of shellac and pitch obtained from Caroline tar. Comparatively insoluble in common organic liquids and acid-resistant. Available in sticks
Myvawax S	70	10^{-6} at 20° C	Soft hydrocarbon wax which is soluble in petroleum ether, CCl_4 and benzene. Unaffected by acetone, alcohol and pump oils
Picein	50	10^{-6} at 20° C	Flows free at 80° C. Yields sufficiently at 15° C to prevent cracking in use. Soluble in benzol and turpentine. Inert to alcohol and inorganic acids. Available in sticks; used like the Apiezon W wax
Silver chloride	Applied at 450° C	Negligible at 20° C	Useful sealing cement for withstanding high temperatures; used for sealing small flat windows on glass tubes, seals into discharge tubes. Soluble in sodium thiosulphate
Zinc oxychloride			Dental cement: 60% zinc chloride with zinc oxide powder mixed in form of thick paste

IX. VALVES

Valves are an important component in any vacuum system since they provide the means for varying the conductance of portions of the system. Thus, they are used for isolating components or controlling the flow of gas in the system.

A. ORDINARY SYSTEMS (10^{-6} torr)

1. Stopcocks

Ground glass stopcocks are the standard valves used in most ordinary glass transfer lines. They may be obtained in a great variety of sizes and shapes. A low vapor pressure grease is normally used to lubricate them. Care must be taken to outgas the grease by rotating the stopcock bore many times when it is under vacuum. Ground or lapped metal stopcocks are sometimes used.

2. Metal-Rubber Valves

A large number of different metal valves exist which employ rubber or plastic materials as packings or seats. These include the gate valve, the diaphragm valve, and the ball valve. Brass or bronze is a common material of construction.

B. LOW VAPOR PRESSURE VALVES

The valves listed in A may not be used in ultrahigh vacuum systems because they contain materials with a high vapor pressure. The valves described in this section are made from low vapor pressure materials and may be used in either ordinary or ultrahigh vacuum systems.

1. Metal Valves

The sealing in these valves is accomplished by compression of a metal, shearing of a metal, or by actual melting of a metal. Motion is achieved with a flexible bellows or diaphragm, which is welded or brazed to the valve body.

(a) Alpert developed the first ultrahigh vacuum valve. In his valve a highly polished Kovar nose was forced into a copper cup. Bills and Allen improved on this design. They forced a silver gasketed monel nose into a monel cup. Their valve is marketed by the Granville-Phillips Company. Young has demonstrated that inexpensive stainless steel Hoke valves may be used in bakeable systems.

Many of the larger metal valves (6-inch diameter up to 14-inch diameter) actually shear the valve seat material (usually copper). In this manner a fresh seat is generated at each closure.

(b) Indium and other low melting, low vapor pressure metals have been used as valve seat materials. They have also been used for a working fluid in cut-offs.

(c) Silver chloride has been used as a valve seat material.

(d) Flattened tubes have been used as crude variable valves. A clamping device, such as a C-clamp, is used to alter their conductance.

2. Glass Valves

Glass valves generally take the form of carefully lapped spherical or planar surfaces. They are used to alter conductance. Magnetic coupling to an iron slug incorporated in the valve is the usual method of operation.

A thin glass membrane or tube and a metal-enclosed-in-glass hammer are commonly used separators. Once opened, this "valve" remains open.

3. Diffusion Leaks

A third class of valves depends on the rate of diffusion of a gas through a material. These are called diffusion leaks.

(a) Porous Rods

Hagstrum has used porous ceramic rods as leaks. The rod was partially surrounded with mercury. The leak rate was controlled by varying the height of the mercury.

(b) Metal Tubes

It is well known that some gases will diffuse through metals and glasses and that the rate of diffusion is a sensitive function of temperature. A number of valves or leaks operate on this principle. They take the form of a thimble or closed tube connected to the vacuum system. The tube is surrounded by a heater wire so that its temperature can be controlled. Palladium and nickel tubes have been used for hydrogen and deuterium leaks, silver for oxygen, and Vycor for helium.

C. REFERENCES

Pirani and Yarwood, op. cit.

Roberts and Vanderslice, op. cit.

J.R. Young and N.R. Whetten

"Techniques for The Admission of High Purity Gases to a Vacuum System"
Trans. Natl. Vacuum Symposium, 1961, 625 (published 1962)

X. MATERIALS OF CONSTRUCTION

Unfortunately time does not allow us to go into any great detail on the properties of the materials of construction used in vacuum technology. General references on materials and techniques are listed on page 4 of these notes. Materials of construction for ultrahigh vacuum systems are discussed in Chapter 3 of Roberts and Vanderslice, op. cit.

A. GENERAL CONSIDERATIONS

In this section we shall only be concerned with glasses, metals, and ceramics. Rubbers, polymers, greases and other high vapor pressure materials have been briefly discussed in Section VIII-B-2. Vapor pressures, coefficients of expansions, diffusion of gases, outgassing, and chemical stability of materials are all important properties to consider when designing a vacuum system.

B. VAPOR PRESSURE

Vapor pressure data for 79 solid and liquid elements has recently been compiled by R.E. Honig [RCA Review, 23, 567, (1962)]. These data are given in Table XV and Figs. 3 (a), (b), and (c). Melting and vaporization data for these elements are given in Table XVI. Three different vaporization energies are given in many cases. These are ΔH_V , the heat of vaporization at the boiling point; $\Delta H_{S,0}$, the heat of sublimation at 0°K; and $\Delta H_{S,298}$, the heat of sublimation at 298°K. If the gas phase contains more than one species, they are arranged in order of relative abundance.

The vapor pressures of ceramics and glasses are sufficiently low under most vacuum system conditions that they may be neglected.

Only metals and alloys with low vapor pressures should be used in ultrahigh vacuum systems. This precludes the use of brass, soft solders, cadmium, etc.

C. COEFFICIENTS OF EXPANSION

If a system is to experience temperature gradients, the coefficients of expansions of the materials used must be considered and in many cases carefully matched. The linear expansion of some metals, glasses, and ceramics are given

in Figs. 4, 5, and 6. Values for other materials can be found in the Handbook of Chemistry and Physics.

D. PERMEATION OF GASES

Some gases permeate a variety of materials. Norton has summarized (Table XVII) the present state of knowledge for gas permeation through glasses, metals, semiconductors, and polymers.

The diffusion of helium through glass is often the limiting factor in determining the ultimate pressure in glass vacuum systems. The diffusion of gases through glass depends both on the nature of the gas and the composition of the glass.

You recall that the selective permeability of metals for gases was used in designing diffusion leaks.

E. OUTGASSING

All materials give off gases when heated. This is called outgassing. This gas can come both from adsorbed impurities on the surface as well as from diffusion of gases from the bulk. The gas may also be due to the decomposition of the material. H_2O , CO , CO_2 , N_2 are gases often evolved when materials are heated in vacuum.

F. REACTIVITY

The reactivity of materials of construction with each other and with respect to the experiment performed in the vacuum must also be taken into account.

Hickmott has shown that hydrogen atoms (atomic hydrogen) produced when hydrogen gas comes in contact with an incandescent filament can react with glass causing the evolution of CO , H_2O , and CH_4 .

A number of people have observed that oxygen will react with carbon impurities in a hot tungsten filament to produce CO .

Cesium will react with glass-metal oxide seals causing them to leak.

It is also found that the stability of surface-to-surface contact of many refractory materials fails at high temperatures in vacuum.

G. REFERENCES

See page 4.

TABLE XV

Vapor Pressure Data for 79 Solid and Liquid Elements
[from R. E. Honig, RCA Review, 23, 574 (1962)]

SYMBOL	ELEMENT	CURVE SHEET	REFERENCE	DATA TEMP. RANGE, °K	TEMPERATURES (°K) FOR VAPOR PRESSURES (TORR)														
					10 ⁻¹¹	10 ⁻¹⁰	10 ⁻⁹	10 ⁻⁸	10 ⁻⁷	10 ⁻⁶	10 ⁻⁵	10 ⁻⁴	10 ⁻³	10 ⁻²	10 ⁻¹	1	10 ¹	10 ²	10 ³
Ac	ACTINIUM	C	28	1873, EST.	1045	1100	1160	1230	1305	1390	1490	1605	1740	1905	2100	2350	2660	3030	3510
Ag	SILVER	A	34,58,81	958-2200	721	759	800	847	899	958	1025	1105	1195	1300	1435	1605	1815	2100	2490
Al	ALUMINUM	A	46	1220-1468	815	860	906	958	1015	1085	1160	1245	1355	1490	1640	1830	2050	2370	2800
Am	AMERICIUM	C	11	1103-1453	712	752	797	848	905	971	1050	1140	1245	1375	1540	1745	2020	2400	2970
As ₄	ARSENIC (s)	A	75	EST.	323	340	358	377	400	423	447	477	510	550	590	645	712	795	900
At ₂	ASTATINE	C	75	EST.	221	231	241	252	265	280	296	316	338	364	398	434	480	540	620
Au	GOLD	A	43	1073-1847	915	964	1020	1080	1150	1220	1305	1405	1525	1670	1840	2040	2320	2680	3130
B	BORON	A	46	1781-2413	1335	1405	1480	1555	1640	1740	1855	1980	2140	2300	2520	2780	3100	3500	4000
Ba	BARIUM	C	43	1333-1419	450	480	510	545	583	627	675	735	800	883	984	1125	1310	1570	1930
Be	BERYLLIUM	B	46	1103-1552	832	878	925	980	1035	1105	1180	1270	1370	1500	1650	1830	2080	2390	2810
ΣBi	BISMUTH	A	43		510	540	568	602	640	682	732	790	860	945	1050	1170	1350	1570	1900
ΣC	CARBON (s)	A	24,46	1820-2700	1695	1765	1845	1930	2030	2140	2260	2410	2560	2730	2930	3170	3450	3780	4190
Ca	CALCIUM	A	43	730-1546	470	495	524	555	590	630	678	732	795	870	962	1075	1250	1475	1800
Cd	CADMIUM	A	43	411-1040	293	310	328	347	368	392	419	450	490	538	593	665	762	885	1060
Ce	CERIUM	C	43	1611-2038	1050	1110	1175	1245	1325	1420	1525	1650	1795	1970	2180	2440	2780	3220	3830
Co	COBALT	A	43,79	1363-1522	1020	1070	1130	1195	1265	1340	1430	1530	1655	1790	1960	2180	2440	2790	3220
Cr	CHROMIUM	B	43	1273-1557	960	1010	1055	1110	1175	1250	1335	1430	1540	1670	1825	2010	2240	2550	3000
ΣCs	CESIUM	A	43	300-955	213	226	241	257	274	297	322	351	387	428	482	553	643	775	980
Cu	COPPER	A	43	1143-1897	855	895	945	995	1060	1125	1210	1300	1405	1530	1690	1890	2140	2460	2920
Dy	DYSPROSIUM	C	42,43	1258-1773	760	801	847	898	955	1020	1090	1170	1270	1390	1535	1710	1965	2300	2780
Er	ERBIUM	C	43	1773, EST.	779	822	869	922	981	1050	1125	1220	1325	1450	1605	1800	2060	2420	2920
Eu	EUROPIUM	C	43	696-900	469	495	523	556	592	634	682	739	805	884	981	11100	1260	1500	1800
Fr	FRANCIUM	C	75	EST.	198	210	225	242	260	280	306	334	368	410	462	528	620	760	980
Fe	IRON	A	36,43	1356-1889	1000	1050	1105	1165	1230	1305	1400	1500	1615	1750	1920	2130	2390	2740	3200
Ga	GALLIUM (l)	A	14	1179-1383	755	796	841	892	950	1015	1090	1180	1280	1405	1555	1745	1980	2300	2730
Gd	GADOLINIUM	C	75	EST.	880	930	980	1035	1100	1170	1250	1350	1465	1600	1760	1955	2220	2580	3100
ΣGe	GERMANIUM	B	75	1510-1885	940	980	1030	1085	1150	1220	1310	1410	1530	1670	1830	2050	2320	2680	3180

NOTE: ⊙ indicates melting point.

Table XV (continued)

SYMBOL	ELEMENT	CURVE SHEET	REFERENCE	DATA TEMP. RANGE, °K	TEMPERATURES (°K) FOR VAPOR PRESSURES (TORR)															
					10 ⁻¹¹	10 ⁻¹⁰	10 ⁻⁹	10 ⁻⁸	10 ⁻⁷	10 ⁻⁶	10 ⁻⁵	10 ⁻⁴	10 ⁻³	10 ⁻²	10 ⁻¹	1	10 ¹	10 ²	10 ³	
Hf	HAFNIUM	C	55,59	2035-2277	1505	1580	1665	1760	1865	1980	2120	2270	2450	2670	2930	3240	3630	4130	4780	
Hg	MERCURY	A	43,46	193- 575	170	180	190	201	214	229	246	266	289	319	353	398	458	535	642	
Ho	HOLMIUM	C	16	923-2023	779	822	869	922	981	1050	1125	1220	1325	1450	1605	1800	2040	2410	2910	
In	INDIUM (ℓ)	A	43,54	646-1348	641	677	716	761	812	870	937	1015	1110	1220	1355	1520	1740	2030	2430	
Ir	IRIDIUM	A	37,60,62	1986-2600	1585	1665	1755	1850	1960	2080	2220	2380	2560	2770	3040	3360	3750	4250	4900	
K	POTASSIUM	B	43,76	373-1031	247	260	276	294	315	338	364	396	434	481	540	618	720	858	1070	
La	LANTHANUM	A	1	1655-2167	1100	1155	1220	1295	1375	1465	1570	1695	1835	2000	2200	2450	2760	3150	3680	
Li	LITHIUM	A	43	735-1353	430	452	480	508	541	579	623	677	740	810	900	1020	1170	1370	1620	
Lu	LUTETIUM	C	80	EST.	1000	1060	1120	1185	1260	1345	1440	1550	1685	1845	2030	2270	2550	2910	3370	
Mg	MAGNESIUM	A	43	626-1376	388	410	432	458	487	519	555	600	650	712	782	878	1000	1170	1400	
Mn	MANGANESE	B	81	1523-1823	660	695	734	778	827	884	948	1020	1110	1210	1335	1490	1695	1970	2370	
Mo	MOLYBDENUM	B	43	2070-2504	1610	1690	1770	1865	1975	2095	2230	2390	2580	2800	3060	3390	3790	4300	5020	
Na	SODIUM	B	43	496-1156	294	310	328	347	370	396	428	466	508	562	630	714	825	978	1175	
Nb	NIوبيUM	B	73	2304-2596	1765	1845	1935	2035	2140	2260	2400	2550	2720	2930	3170	3450	3790	4200	4710	
Nd	NEODYMIUM	C	43	1240-1600	846	895	945	1000	1070	1135	1220	1320	1440	1575	1770	2000	2300	2740	3430	
Ni	NICKEL	B	43	1307-1895	1040	1090	1145	1200	1270	1345	1430	1535	1655	1800	1970	2180	2430	2770	3230	
Os	OSMIUM	A	61	2300-2800	1875	1965	2060	2170	2290	2430	2580	2760	2960	3190	3460	3800	4200	4710	5340	
P ₄	PHOSPHORUS (s)	A	75		283	297	312	327	342	361	381	402	430	458	493	534	582	642	715	
Pb	LEAD	B	43	1200-2028	516	546	580	615	656	702	758	820	898	988	1105	1250	1435	1700	2070	
Pd	PALLADIUM	A	21,38	1294-1640	945	995	1050	1115	1185	1265	1355	1465	1590	1735	1920	2150	2450	2840	3380	
ΣPo	POLONIUM	B	31,75	711-1286	332	348	365	384	408	432	460	494	537	588	655	743	862	1040	1250	
Pr	PRASEODYMIUM	C	43	1423-1693	900	950	1005	1070	1140	1220	1315	1420	1550	1700	1890	2120	2420	2820	3370	
Pt	PLATINUM	A	21,37,43	1697-2042	1335	1405	1480	1565	1655	1765	1885	2020	2180	2370	2590	2860	3190	3610	4170	
Pu	PLUTONIUM (ℓ)	C	63	1392-1793	931	983	1040	1105	1180	1265	1365	1480	1615	1780	1975	2230	2550	2980	3590	
Ra	RADIUM	C	75	EST.	436	460	488	520	552	590	638	690	755	830	920	1060	1225	1490	1840	
Rb	RUBIDIUM	B	75		227	240	254	271	289	312	336	367	402	446	500	568	665	802	1000	
Re	RHENIUM	A	43	2494-2999	1900	1995	2100	2220	2350	2490	2660	2860	3080	3340	3680	4080	4600	5220	6050	

Table XV (continued)

SYMBOL	ELEMENT	CURVE SHEET	REFERENCE	DATA TEMP. RANGE, °K	TEMPERATURES (°K) FOR VAPOR PRESSURES (TORR)														
					10 ⁻¹¹	10 ⁻¹⁰	10 ⁻⁹	10 ⁻⁸	10 ⁻⁷	10 ⁻⁶	10 ⁻⁵	10 ⁻⁴	10 ⁻³	10 ⁻²	10 ⁻¹	1	10 ¹	10 ²	10 ³
Rh	RHODIUM	B	22,37,43,60	1709-2205	1330	1395	1470	1550	1640	1745	1855	1980	2130	2310	2520	2780	3110	3520	4070
Ru	RUTHENIUM	B	43,61	2000-2500	1540	1610	1695	1780	1880	1990	2120	2260	2420	2620	2860	3130	3480	3900	4450
SS	SULFUR	A	10,46,52		230	240	252	263	276	290	310	328	353	382	420	462	519	606	739
SSb	ANTIMONY	B	5,44,67	693-1110	477	498	526	552	582	618	656	698	748	806	885	1010	1250	1560	1960
Sc	SCANDIUM	B	1,48	1301-1780	881	929	983	1045	1110	1190	1280	1380	1505	1650	1835	2070	2370	2780	3360
SSe	SELENIUM	B	29,45,53	550-950	286	301	317	336	356	380	406	437	472	516	570	636	719	826	972
SSi	SILICON	B	6,18,33	1640-2054	1090	1145	1200	1265	1340	1420	1510	1610	1745	1905	2090	2330	2620	2990	3490
Sm	SAMARIUM	C	43	789-833	542	573	608	644	688	738	790	853	926	1015	1120	1260	1450	1715	2120
Sn	TIN (ℓ)	B	43	1424-1753	805	852	900	955	1020	1080	1170	1270	1380	1520	1685	1885	2140	2500	2960
Sr	STRONTIUM	B	75		433	458	483	514	546	582	626	677	738	810	900	1005	1160	1370	1680
Ta	TANTALUM	B	43	2624-2948	1930	2020	2120	2230	2370	2510	2680	2860	3080	3330	3630	3980	4400	4930	5580
Tb	TERBIUM	C	80	EST.	900	950	1005	1070	1140	1220	1315	1420	1550	1700	1890	2120	2420	2820	3370
Tc	TECHNETIUM	C	75	EST.	1580	1665	1750	1840	1950	2060	2200	2350	2530	2760	3030	3370	3790	4300	5000
Te ₂	TELLURIUM	A	51,56	481-1128	366	385	405	428	454	482	515	553	596	647	706	791	905	1065	1300
Th	THORIUM	A	17	1757-1956	1450	1525	1610	1705	1815	1935	2080	2250	2440	2680	2960	3310	3750	4340	5130
Ti	TITANIUM	B	43,46	1510-1822	1140	1200	1265	1335	1410	1500	1600	1715	1850	2010	2210	2450	2760	3130	3640
Tl	THALLIUM	B	5,30	519-924	473	499	527	556	592	632	680	736	803	882	979	1100	1255	1460	1750
Tm	THULIUM	C	43	809-1219	624	655	691	731	776	825	882	953	1030	1120	1235	1370	1540	1760	2060
U	URANIUM	C	2, 4, 65	1630-2071	1190	1255	1325	1405	1495	1600	1720	1855	2010	2200	2430	2720	3080	3540	4180
V	VANADIUM	B	43	1666-1882	1235	1295	1365	1435	1510	1605	1705	1820	1960	2120	2320	2560	2850	3220	3720
W	TUNGSTEN	B	43,46	2518-3300	2050	2150	2270	2390	2520	2680	2840	3030	3250	3500	3810	4180	4630	5200	5900
Y	YTTRIUM	A	1	1774-2103	1045	1100	1160	1230	1305	1390	1490	1605	1740	1905	2105	2355	2670	3085	3650
Yb	YTERBIUM	C	77	EST.	436	460	488	520	552	590	638	690	755	830	920	1060	1225	1490	1840
Zn	ZINC	A	5,43,67	422-1089	336	354	374	396	421	450	482	520	565	617	681	760	870	1010	1210
Zr	ZIRCONIUM	C	46	1949-2054	1500	1580	1665	1755	1855	1975	2110	2260	2450	2670	2930	3250	3650	4170	4830

TABLE XVI

Melting and Vaporization Data for 79 Solid and Liquid Elements
 [from R. E. Honig, RCA Review, 23, 567 (1962)]

SPECIES	MELTING			VAPORIZATION				
	MP °K	ΔH_M kcal/mole	REF.	BP °K	ΔH_V -BP kcal/mole	$\Delta H_{S,0}$ -0°K kcal/mole	$\Delta H_{S,298}$ -298°K kcal/mole	REF.
Ac	1320 ± 50	(3.4)	50,74	3470 ±300	(95)			28
Ag	1234	2.885	43,50	2435		67.99 ±.3	68.10 ±.3	43,58,81
Ag ₂						98		25
Al	932 ±1	2.55 ±.05	46	2736	70.7 ±.4	77.4 ±.4	78.0 ±.4	46
Al ₂						109		13
Am	<1103 1269		11 9	2880 2700	57.		66	11 9
As ₄ As ₂ As	1090	6.62	75	886	30.5		34.5 >48 >69	75
At ₂	(575)	(5.7)	75	(610)	(21.6)			75
Au	1336	2.955	43	3081		88.0 ±1.0	88.0 ±1.0	26,34,39,43,57,64
Au ₂						126		25
B	2300 >2420	5.3	46 70	3950		128.0 - 136.7	129.2 - 137.9	3,12,27,32,46, 62,66,69,70,78
B ₂						190 - 199	191 - 200	
Ba	983	1.83	50	1895	36.7		41.74	43
Be	1556	2.8 ±.5 3.52 ±.08	46 47	2757	71.14	77.25 ±.5	78.25 ±.5	46
Bi ₂ Bi	544.5	2.6 ±.1	43	1852		53.12 49.56	52.50 49.50	43 43
C ₃ C C ₂ C ₄ C ₅			4130			188.1 ±2.3 169.58 ±.45 195.8 ±1.7 230 ±6 233 ±6	189.7 ±2.3 170.89 ±.45 199 ±1.7 242 ±6 242 ±6	24,46
Ca	1123	1.97	43	1756		42.26 ±.4	42.37 ±.4	43
Ca ₂							79	8
Cd	594	1.46 ±.03	43	1040	22.96	26.78 ±.15	26.77 ±.15	5,43
Cd ₂							50.8	8
Ce	1077	1.238 ±.004	72	(3740)	92.9 (±1800)		97 ±3	43

Table XVI (continued)

SPECIES	MELTING			VAPORIZATION				
	MP °K	ΔH_M kcal/mole	REF.	BP °K	ΔH_V @BP kcal/mole	$\Delta H_{S,0}$ @0°K kcal/mole	$\Delta H_{S,298}$ @298°K kcal/mole	REF.
Co	1768 ±1	4.1	43	3174		101.1 ±1.0	101.5 ±1.0	43
Cr	2176	(5.0)	43	2938		94.3 ±.5	94.9 ±.5	43
Cs	301.8	0.52 ±.02	43	955		19.05 ±.07	18.67 ±.07	43
Cs ₂						27.70	26.62	43
Cu	1357	3.12 ±.15	43	2846		80.25	80.53	43
Cu ₂						114		25
Dy	1680 ±5	(4.1)	15	2710	62.5		71.4 61.6	42,43 68 80
Er	1770 ±15	(4.1)	15	(2850)		75.67 ±.34	75.39 ±.34 66.4	43,77 80
Eu	1099 ±10	(2.5)	43	1764		43.4 ±.4	43.11 ±.25	43,77
Fr	(300)	(0.5)	75	(950)	(15.2)			75
Fe	1809	3.63 ±.6	43	3148		98.99 ±.20 100.5 ±.4	99.55 ±.20	43 36
Ga	302.9	1.335	43	2676			68.96 ±.19	14
Ga ₂							106	13
Gd	1585 ±15	(3.7)	71,75	(3000)		81.91 ±.32	81.22 ±.32 83.6	75,77 80
Ge	1210	7.6	75	3100	79.9		90.	75
Ge ₂							115	25
Hf	>2400	(5.2)	59,75	4690 4800			145.5 ±1.0 146.59 ±.24	42,59 42,55
Hg	234.29	0.5486	43,46	629.73	14.171	15.441 ±.013	14.691 ±.013	43,46
Hg ₂							27.4	8
Ho	1734 ±5	4.6 ±.6	16	2842		75.47 ±.44	70.6 ±.7 75.04 ±.44	16,80 77
In	429.3	0.78	43	2364			58 ±2	43,54
In ₂							94	20

Table XVI (continued)

SPECIES	MELTING			VAPORIZATION				
	MP °K	ΔH_M kcal/mole	REF.	BP °K	ΔH_V @BP kcal/mole	$\Delta H_{S,0}$ @0°K kcal/mole	$\Delta H_{S,298}$ @298°K kcal/mole	REF.
Ir	2727	(6.3)	50	4810 ± 100			159.9 ± 2.0	37,60,62
K	336.4 ± 1	0.562 ± 0.006	43	1031	19.176 ± 0.053	21.629 ± 0.050	21.415 ± 0.050 30.37 ± 0.50	43,76 43
K ₂								
La	1193	(1.29)	43	3610		104.1 ± 7 100.24 ± 9	104.0 ± 7 100.18 ± 9	1 43
Li	453.69 ± 0.3	0.717 ± 0.005	43	1597	35.403 ± 0.400	38.164 ± 0.400	38.584 ± 0.400 50.41 ± 0.90	43 43
Li ₂								
Lu	1925 ± 5	(4.6)	15,43	(3300)			102.8 94.7	35,77 80
Mg	923	2.14 ± 0.5	43,46	1376		35.01 ± 0.25	35.3 ± 0.25	43
Mn	1517	3.5	75	2309		66.45 ± 0.5	66.74 ± 0.5	81
Mo	2890	(6.65)	43	4924		158.3 ± 8	158.7 ± 8	43
Na	370.98 ± 0.2	0.6217 ± 0.0010	43	1156.2	23.426 ± 0.150	25.901 ± 0.150	25.852 ± 0.150 33.4	43 8
Na ₂								
Nb	2770	(6.4)	73	4640		171.80 ± 49	172.53 ± 49	73
Nd	1297	1.705 ± 0.019	43	3335		77.5 ± 2.0	77.3 ± 2.0 76.3	43 80
Ni	1725 ± 4	(4.21)	43	3159		102.18 ± 1.4	102.67 ± 1.4	43
Os	3318	(7.0)	61,75	5260			187.4 ± 9	61
P ₄	870	4.5 ± 2	46	704			30.77 ± 0.40	46
P ₂							42.7	75
P							79.8	75
Pb	600.6	1.14	43	2016		46.76 ± 30	46.60 ± 30	43
Pb ₂							70	25
Pd	1823 ± 3	4.2	43	3310		89.0 ± 8	89.2 ± 8 91.0 ± 8	21 38

Table XVI (continued)

SPECIES	MELTING			VAPORIZATION				
	MP °K	ΔH_M kcal/mole	REF.	BP °K	ΔH_V BP kcal/mole	$\Delta H_{S,0}$ °K kcal/mole	$\Delta H_{S,298}$ °K kcal/mole	REF.
Po ₂ Po	527	(3.0)	50	1220			32.9 34.5	31,75 75
Pr	1208	1.65	35	3295			85.1 77.9	68 80
Pt	2043	(4.7)	43	4097		134.8 ±1.0	135.0 ±1.0	43,21,37
Pu	913		19	3508 ±19	80.46 ±.32 (+1592)			63
Ra	973	(2.0)	75	(1800)	(32.7)			75
Rb	312	0.56	75	974	16.54		19.60 27.55	75 75
Rb ₂								
Re	3453 ±20	(7.9)	43	5960	169.	185.9 ±2.0	186.1 ±2.0	43
Rh	2239	(5.15)	43	4000 ±100		132.8 ±.5	133.1 ±.5	43
Ru	(2700)	(6.1)	43	4392 ±100			154.9 ±1.3	43,61
S ₈ S ₂ S	388.36	0.41052	46	717.75	2.3		24.35 30.84 66	10,75 75 8
Sb ₄ Sb ₂ Sb	903	4.69 ±.10	43	1908		50.2 56.8 62.6	49.0 56.3 62.7	43 43 43
Sc	1811 ±2	4.2	35	3280		79.7 ±0.4	82.28	1 48
Se ₆ Se ₂ Se	490	1.3	75	952	6.29 kcal/g-at		35.38 34.12 55	75 75 23
Si Si ₂ Si ₃	1685 ±2	12.095 ±.1	46	3418			107.4 ±3.0 140 146	6,18,33 25 46
Sm	1345	2.061 ±.015	43	2076		49.42 ±.60	49.56 ±.60	43
Sn Sn ₂	505	1.75	43	2891		72.1 ±.5	72.1 ±.5 98	43 25
Sr	1043	(2.2)	75	1640	33.2		39.1	75
Ta	3270	(7.5)	75	5510		186.8 ±.6	186.9 ±.6	43
Tb	1638	3.9	43,50	(3295)			87.1 91.9	80 77

Table XVI (continued)

SPECIES	MELTING			VAPORIZATION				
	MP °K	ΔH_M kcal/mole	REF.	BP °K	ΔH_V @BP kcal/mole	$\Delta H_{S,0}$ @0°K kcal/mole	$\Delta H_{S,298}$ @298°K kcal/mole	REF.
Tc	(2400)	(5.5)	75	(4900)	(138)		(155)	75
Te ₂	723	4.18	75	1267			35.6	75
Te							46.5	75
Th	1968	(3.74)	75	5020			136.6 ±.5	17
Ti	1940	4.46	43	3575		112.08 ±.50	112.74 ±.50	43
Tl	577	0.975 ±.050	43	1710		42.85 ±.20	42.70 ±.20	5,30
Tm	1873 ±50	4.4	43	2005			58.8 ±.2	43
U	1405.5 ±.8	4.7 ±.2	7,65	4090	106.8	116.6 ±.1	117.2 ±.1	2,65
V	2190 ±10	(5.05)	43	3652		122.37 ±.30	123.17 ±.30	43
W	3650 ±5	8.42	43,46	5800		201.5 ±2.0	201.8 ±2.0	43,46
Y	(1773)	(4.1)	75	3570		97.6 ±.4	85.71	1 49
Yb	1097 ±5	2.2	50	(1800)			40.0	68
Zn	692.7 ±.1	1.765 ±.080	43	1184		31.11 ±.05	31.25 ±.05	43
Zr	2128 ±25	(4.9)	43,46	4747	136.4	145.1 ±.4	145.4 ±.4	46

TABLE XVII

General Features of Gas Permeation

[from F.J. Norton, Natl. Symposium Vacuum Technol. Trans.
1961, 8 (Pub. 1962)]

<u>Glasses</u>	<u>Metals</u>	<u>Semiconductors</u>	<u>Polymers</u>
He, H ₂ , D ₂ Ne, Ar, O ₂ measurable through SiO ₂	No rare gas through any metal	He and H ₂ through Ge and Si	All gases permeate all polymers
Vitreous silica fastest	H ₂ permeates most, especially Pd	Ne, Ar not measurable	Water rate apt to be high
	O ₂ permeates Ag		Many specifi- cities
	H ₂ through Fe by corrosion, elec- trolysis, etc.		
All rates vary as pressure directly	Rates vary as $\sqrt{\text{pressure}}$	H ₂ rate varies as $\sqrt{\text{pressure}}$	All rates vary as pressure directly

In all, rate is an exponential function of temperature for true permeation.

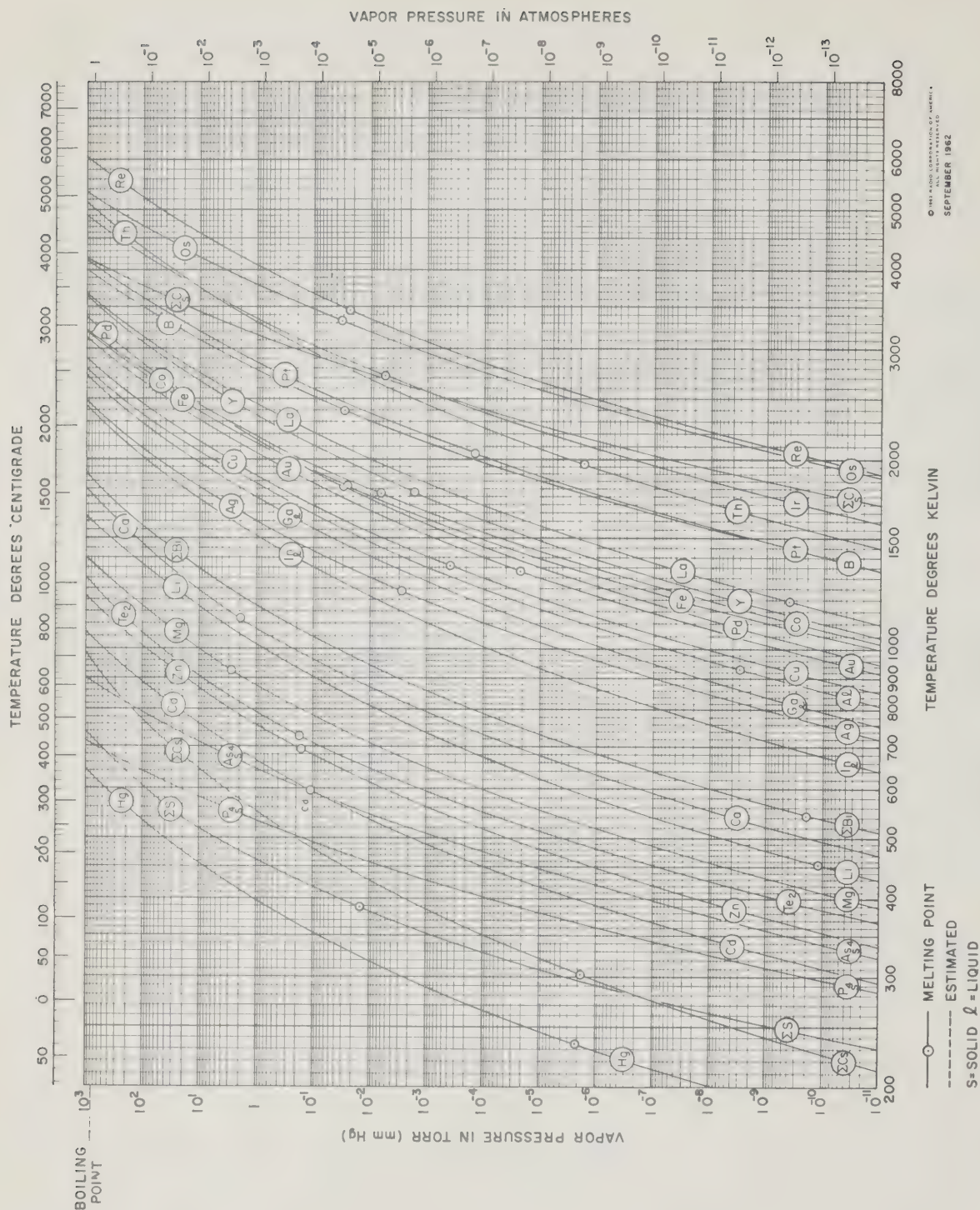


Fig. 3(a) Vapor pressure data for 79 solid and liquid elements [from R. E. Honig, RCA Review, 23, 567 (1962)].

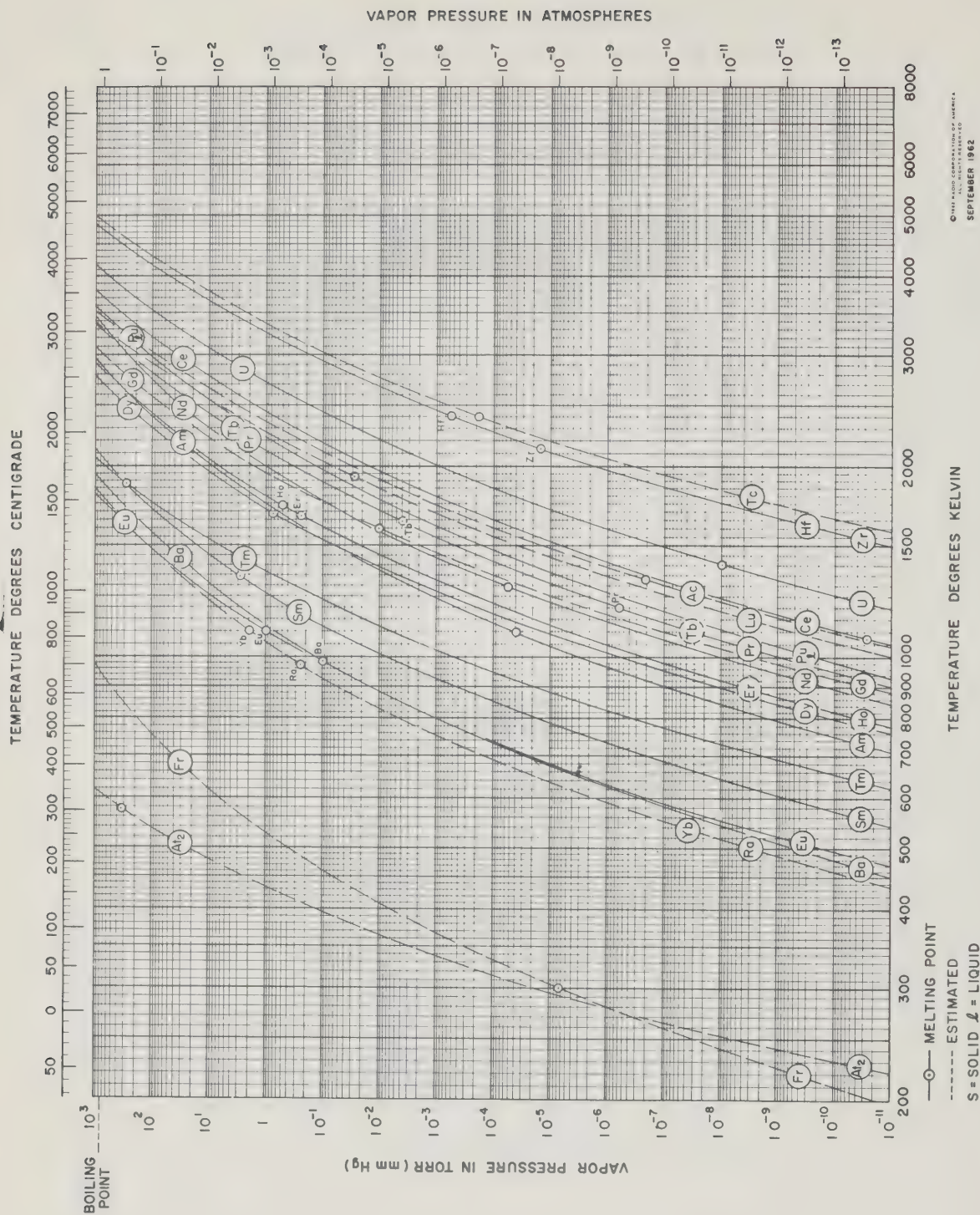


Fig. 3(c) Vapor pressure data for 79 solid and liquid elements [from R. E. Honig, RCA Review, 23, 567 (1962)].

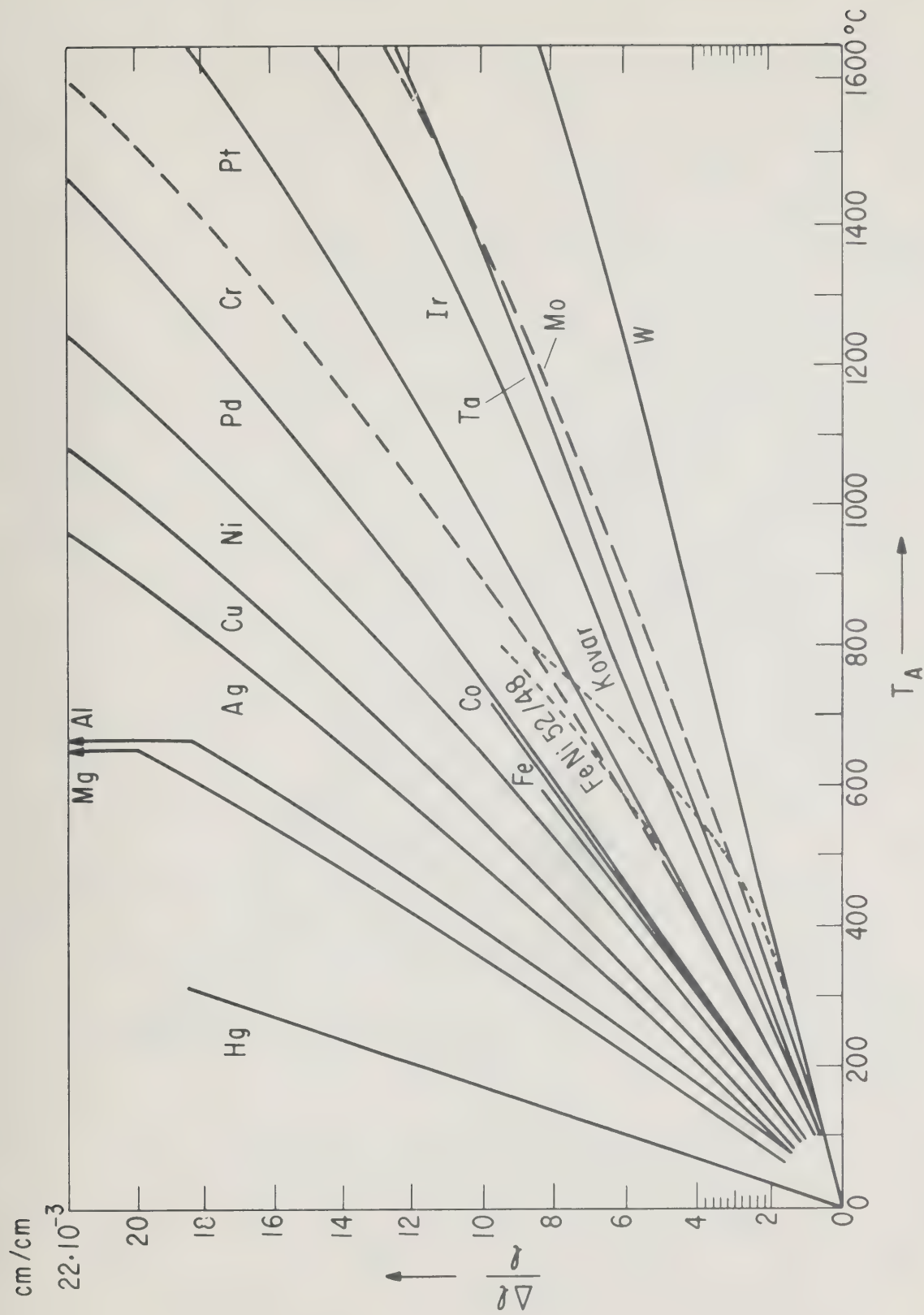


Fig. 4 Coefficient of linear expansion of some common metals and alloys (from W. Espe, Werkstoffkunde der Hochvakuumtechnik, op. cit.).

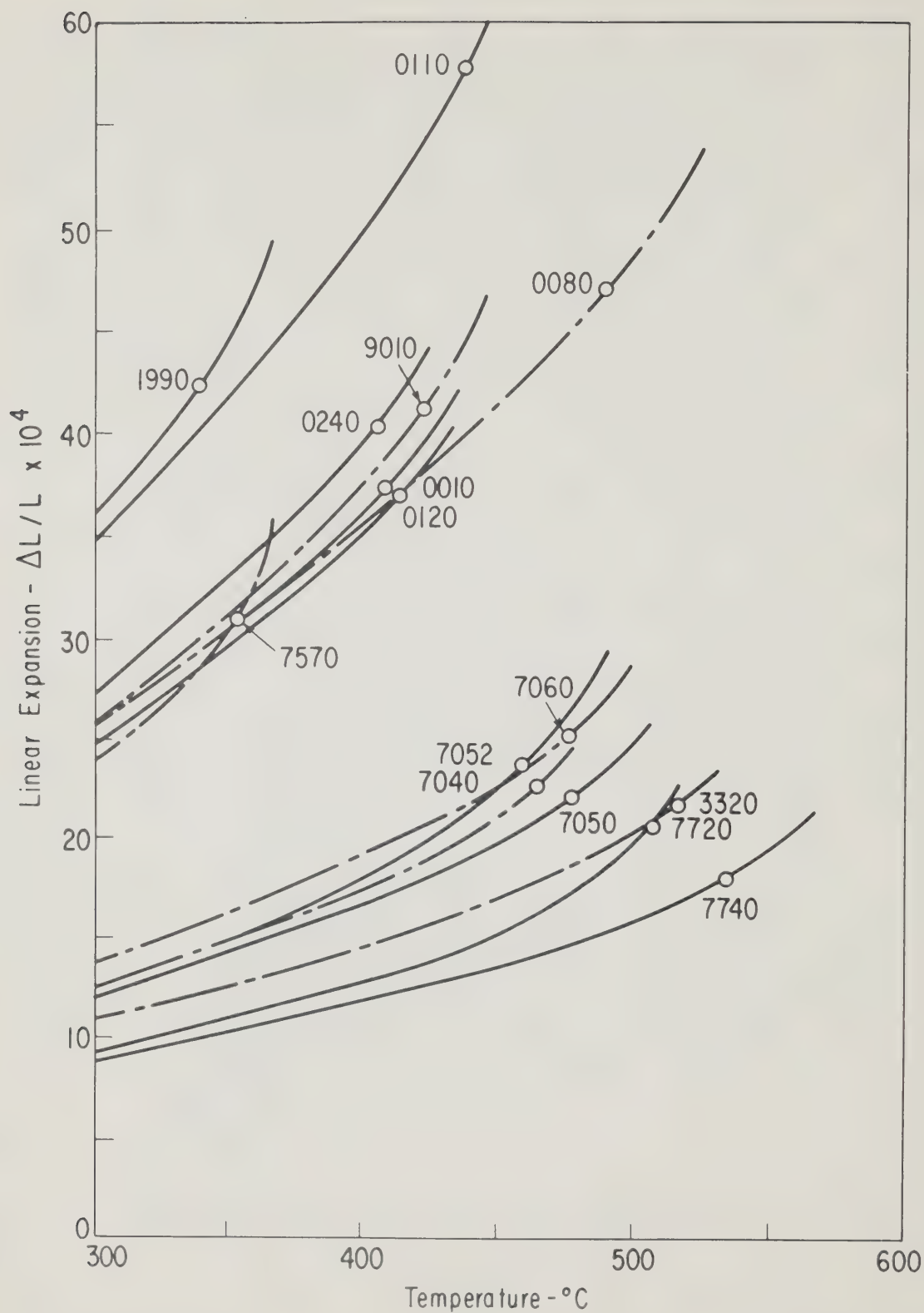


Fig. 5 Coefficient of linear expansion for some Corning glasses (from E. B. Shand, Glass Engineering Handbook, op. cit.).

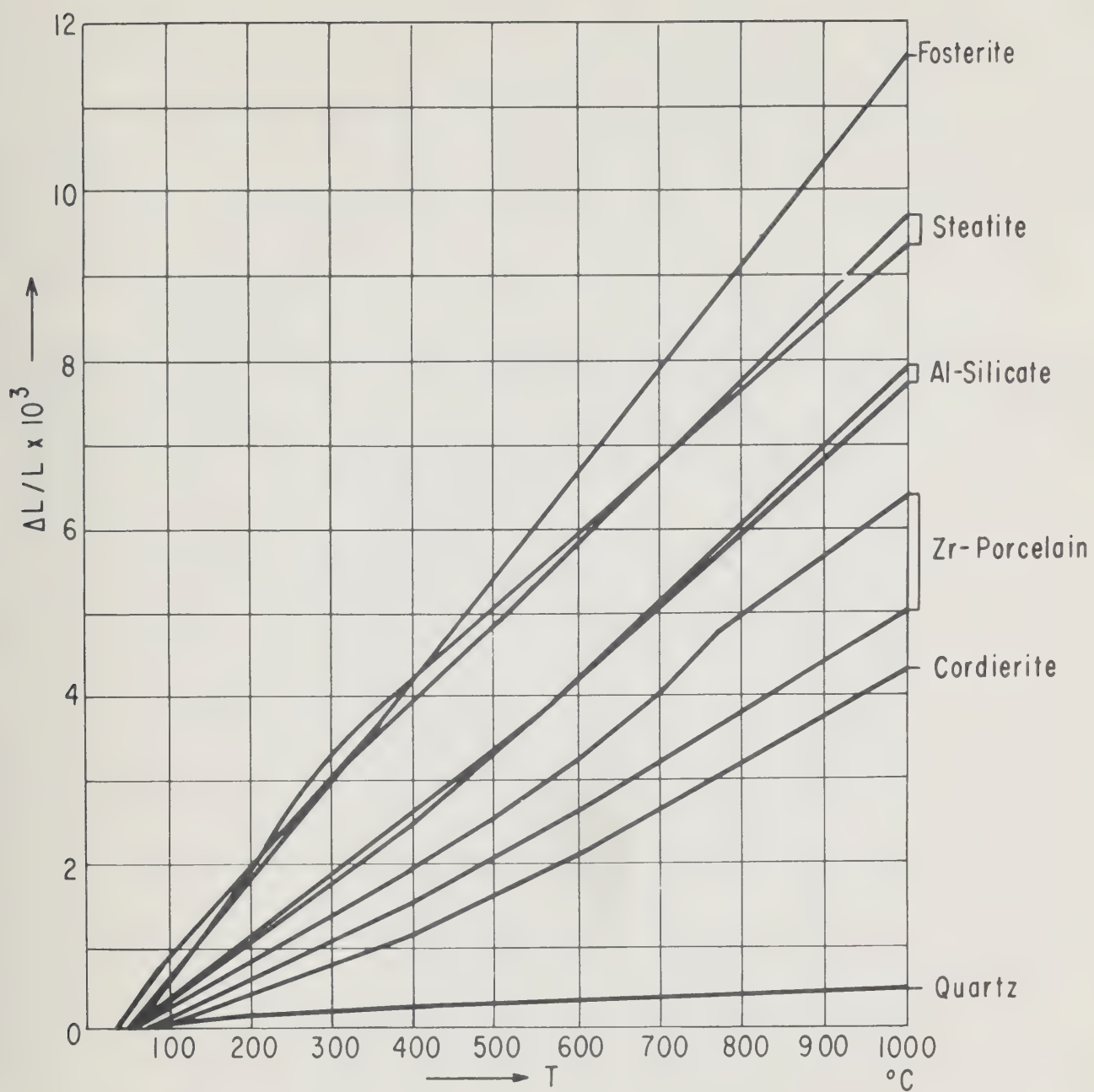


Fig. 6 Coefficient of linear expansion for several ceramic materials (from W. Espe, Werkstoffkunde der Hochvakuumtechnik, op. cit.).

XI. SYSTEM DESIGN

The design of a vacuum system is dictated by the nature of the experiment to be performed. Systems can be classified as static or dynamic. Dynamic systems have a continuous flow of gas into the system from a real leak. Static systems are usually closed systems, but may have virtual leaks due to outgassing.

High pumping speeds and large conductances are usually associated with dynamic systems.

Systems are also classified according to their ultimate pressure. Ordinary systems usually contain high vapor pressure materials like rubber and attain an ultimate pressure of about 10^{-7} torr. Ultrahigh vacuum systems contain no high vapor pressure materials and have ultimate pressures of 10^{-10} torr or lower.

We shall discuss a number of typical vacuum systems.

XII. LEAK DETECTION

Searching for leaks is a time-honored past time for all who use high vacuum systems, and can be a frustrating experience for the novice. Often out-gassing of parts in a vacuum system (virtual leaks) appear to be real leaks which cannot be found.

A. PRESSURE TESTING

Pressure testing is a simple rapid method for testing for large leaks ($\sim 4 \times 10^{-2}$ torr liter sec^{-1}) in either glass or metal systems. Several atmospheres of air are applied to the inside of the system. Often air can be heard to hiss through the leak. A soap solution will bubble if placed over the area of the leak.

B. SPARK COIL

Leaks in glass systems which pump down to 10^{-3} to 1 torr can be tested with a spark coil. The spark will run to the hole in the glass and make it appear as a very bright white spot. If the pressure in the glass is high enough to support a discharge, a pink color indicates the presence of air. If acetone is brushed over or CO_2 sprayed over the leak, the color of the discharge will change.

C. THERMOCOUPLE OR PIRANI GAUGE

The thermocouple or Pirani gauge can be used to detect leaks in the pressure range 10^{-3} to 1 torr. Hydrogen or helium is sprayed over the system. When it is sprayed on the leak, it enters the system and causes the gauge to indicate an increase in pressure. This is because the thermal conductivity of H_2 or He is greater than that of air. These gauges can be used to detect leaks as small as $\sim 10^{-5}$ torr liter sec^{-1} .

D. IONIZATION GAUGE

The sensitivities of ionization gauges are a function of the type of gas. Therefore Bayard-Alpert gauges, cold cathode gauges, or Vac Ion pumps may be used to find leaks. A gas such as H_2 or Ar is sprayed on the system, and the leak is found by noting a change in gauge reading. This method can be used over the pressure range of $\sim 10^{-3}$ to 10^{-10} torr and will detect leaks as small as $\sim 10^{-8}$ torr liter sec^{-1} .

E. MASS SPECTROMETER

Mass spectrometers have been widely used as leak detectors. Helium is usually used as a probe gas. It is possible to detect leaks as small as about 10^{-10} torr liter sec⁻¹.

F. REFERENCES

Dushman, op. cit.

Pirani and Yarwood, op. cit.

XIII. DEPOSITION OF FILMS

The deposition of metallic and nonmetallic films on solid substrates is an area of great technological importance. Bracelets, resistors, telescope mirrors, etc. are often coated with thin films.

Methods of deposition include sputtering and evaporation. The sputtering of a metal in a reactive atmosphere leads to the deposition of a compound. This technique, called reactive sputtering is often used for depositing films of metal oxides.

Evaporation is used most frequently. Important parameters in evaporation include the flux of atoms at the substrate and the substrate temperature.

Often metals can be evaporated from a fine wire of the material; other times, tungsten coils or ceramic crucibles are used to contain the material. Figure 7 illustrates some typical evaporation sources.

It is important that substrate materials be carefully cleaned in order to have good adhesion.

Hollana (Vacuum Deposition of Thin Films, John Wiley and Sons, New York, 1956) has compiled a useful list which summarizes techniques and refractory support material for evaporating metals (Table XVIII).

TABLE XVIII

Techniques and Refractory Support Materials for Evaporating Metals,
 Together with Some Useful Vapor-Pressure Data
 (from Dushman, Scientific Foundations of Vacuum Technique, *op. cit.*)

Metal	Melting Point (°C)	Evaporation Temp. (°C), Vapor Pressure = 10 microns Hg*	Resistance Heated Sources in Order of Merit		Other Evaporation Techniques		Remarks
			Filaments†	Boats	Source‡	Method of Heating	
Aluminium	660	996(?) 1148(?)	W, Ta, helical coil	...	...	...	Alloys freely with refractory metals and reacts with carbon and oxide crucibles. Wets Chromel.
Antimony (Sb ₂)	630	678	Chromel, Ta, conical basket	Mo, Ta	Alumina crucible	External W heater	...
Arsenic	...	...	...	...	Alumina crucible	External W heater	...
Barium	717	629	W, Ta, Mo, Cb, Ni, Fe, Chromel, conical basket	Ta, Mo	...	—	Freely wets without alloying with the heater metals quoted. Reacts with alumina.
Beryllium	1284	1246	Ta, W, Mo, conical basket	...	Carbon crucible	Electron bombardment	Wets heater metals quoted.
Bismuth	271	698	Chromel, Ta, W, Mo, Cb, conical basket	Fe, Mo, Ta	BeO crucible Alumina crucible	High frequency External W heater	Wets Chromel.
Boron	2000 —2080	1355	—	...	Carbon	Resistance heated	Deposits from carbon probably impure.
Calcium	810	605	W, conical basket	...	Alumina crucible	External W heater	...
Cadmium	321	264 (subl.)	Chromel, Cb, Ta, Mo, W, Ni, Fe, conical basket	Mo, Ta	Alumina crucible Iron crucible	External W heater Nichrome heater	Freely wets Chromel and Cb.
Carbon	3700 ±100	2681	...	...	Pointed carbon rods pressed together, forming high-resistance contact	Resistance heating	...
Cerium	785	1305	...	...	...	...	...
Cesium	29	153	...	...	...	...	...
Chromium	1900	1205	W, conical basket	...	Electro-deposited Cr on W helical coil	Sublimation	...
Cobalt	1478	1649	Cb, W	...	Alumina or BeO crucible Electro-plated W spiral	Embedded W heater Resistance heater	Alloys with W, Ta, Mo, Cb, Pt. Evaporant weight must not exceed 35 per cent of that of W spiral.
Columbium	2500	(VP at MP = 1 micron Hg)	W, helical coil	...	...	...	Refractory metal used as a source material.
Copper	1083	1273	Pt, helical coil; Cb, Mo, Ta, W, conical basket	Mo, Ta	Alumina crucible	Embedded W heater	Copper alloys with Ni, Fe, Chromel. Does not wet readily Mo, W, Ta.
Gallium	30	1093	...	...	BeO, SiO ₂ , Al ₂ O ₃	...	Alloys with metals, oxides quoted resist attack up to 1000° C.

Table XVIII (continued)

Metal	Melting Point (°C)	Evaporation Temp. (°C), Vapor Pressure = 10 microns Hg*	Resistance Heated Sources in Order of Merit		Other Evaporation Techniques		Remarks
			Filaments†	Boats	Source‡	Method of Heating	
Germanium	959	1251	Ta, Mo, W, conical basket	Mo, Ta	Alumina crucible Carbon crucible	Embedded W heater Resistance heater	Wets Ta and Mo.
Gold	1063	1465	W, Mo, conical basket	Mo	...	...	Wets but reacts with Ta, possible alloy formation. Partially wets W, Mo.
Indium	157	952	W, Fe, conical basket	Mo	...	...	...
Iridium	2454	2556	...	...	...	...	...
Iron	1535	1447	W, helical coil	...	Alumina or BeO crucible	Embedded W heater	Alloys with W, Ta, Mo, Cb. Evaporant must not exceed 35 per cent of the weight of W filament.
Lead	328	718	Fe, Ni, Chromel, conical basket	Mo	Alumina or iron crucible Carbon (?)	External Nichrome heater Resistance heater	Does not wet W, Ta, Mo, and Cb.
Lithium	179	514	...	...	Mild steel (?) crucible	Nichrome heater	...
Magnesium	651	443 (subl)	W, Ni, Fe, Ta, Mo, Cb, Chromel, conical basket	Mo, Ta	Iron crucible Carbon	External Nichrome heater Resistance heater	Does not melt when volatilized from open spirals and boats.
Manganese	1244	980	W, Ta, Mo, Cb, conical basket	...	Alumina crucible	Embedded W heater	Freely wets heater metals quoted.
Molybdenum	2622	2533	...	...	...	...	Refractory metal used for filament and boat-type vapor sources. Evaporates rapidly if oxidized to form MoO ₃ .
Nickel	1455	1510	W, heavy-gauge helical coil	...	Alumina or BeO crucible	Embedded W heater	Alloys with Mo, Ta, and W. Evaporant must not exceed 30 per cent of the weight of W filament.
Palladium	1555	1566	W, helical coil	...	...	...	...
Platinum	1774	2090	Multistrand W filament with Pt wire twisted together	...	Electro-deposited Pt on W spiral	Resistance heater	Alloys with Ta and partially with W. Platinum may be used as a source heater for metal oxides to prevent decomposition of charge.
Rhodium	1967	2149	...	...	Electro-deposited Rh on W spiral Resistance heated Rh foil	Sublimation Sublimation	Requires very low pressure for deposition of neutral transmitting films.
Selenium	217	234	Chromel, Fe, Mo, Cb, conical basket	Mo, Ta	Alumina crucible	Nichrome external heater or radiant heater	Very volatile, may contaminate plant. Wets filament metals quoted.
Silicon	1410	1343	...	...	BeO crucible	Embedded W heater	Difficult to prepare Si films free from SiO contamination.

Table XVIII (continued)

Metal	Melting Point (° C)	Evaporation Temp. (° C), Vapor Pressure = 10 microns Hg*	Resistance Heated Sources in Order of Merit		Other Evaporation Techniques		Remarks
			Filaments†	Boats	Source‡	Method of Heating	
Silver	961	1047	Ta, Mo, Cb, Fe, Ni, Chromel, helical coil or W conical basket	Mo, Ta	Electro-deposited Ag on Mo helical coil	Resistance heater	Ag does not wet W. Can be kept in basket by binding fine platinum wire on outside.
Strontium	771	549	W, Ta, Mo, Cb, conical basket	...	Carbon	Resistance heated	Freely wets without alloying with all filament metals quoted.
Tantalum	2996	(VP = 1 micron Hg at 2820°)	...	...	...	—	Refractory metal used for source heaters.
Tellurium	452	(VP = 760 mm Hg at 1390°)	W, Ta, Mo, Cb, Ni, Fe, Chromel, conical basket	...	Alumina crucible	External Nichrome heater	Very volatile, may lead to plant contamination. Wets without alloying all metal heaters quoted.
Thallium	304	606	Ni, Fe, Cb, Ta, conical basket	...	Alumina crucible	External Nichrome heater	Freely wets metal heaters quoted without alloying. Partially wets W, Ta, but not Mo. Wets W heater.
Thorium	1827	2196	W, conical basket	...	...	—	
Tin	232	1189	Chromel, helical coil; Mo, Ta, conical basket	Mo, Ta	Alumina crucible Carbon	Embedded W heater Resistance heater	Wets Chromel and Mo.
Titanium	1727	1546	W, Ta, conical basket or helical coil	...	Carbon	Resistance heated	Ti reacts with W spiral, deposit contains trace of W. Ti does not react with Ta but filament may burn out during pre-melting of Ti.
Tungsten	3382	3309	...	...	...	...	Refractory metal used for source heaters. Evaporates more readily if surface oxidized to form volatile WO ₃ or WO ₂ .
Uranium	1132	1898	W, conical basket	...	...	...	Forms oxidized deposits at lowest gas pressures.
Vanadium	1697	1888	W, Mo, conical basket	...	...	...	Alloys with Ta and partially with W. Wets but does not alloy with Mo.
Yttrium	1477	1649	...	...	...	...	...
Zinc	419	343 (subl)	W, Ta, Mo, Cb, conical basket	...	Alumina or iron crucible Carbon	External Nichrome heater Resistance heater	Wets without alloy formation all filament metals quoted.
Zirconium	2127	2001	W, conical basket or helical coil	...	...	...	Requires low pressures <0.1 micron Hg to prevent film oxidation. Evap. characteristics similar to Ti.

* Vapor-pressure data are mainly those reported by Dushman. In many cases rapid evaporation will commence only at temperatures well above the values quoted, because of the existence of surface oxide films.

† Suitable filament materials taken from the reports of Cartwright and Strong, Countryman, Caldwell, and Holland.

‡ The preparation of alumina and beryllium oxide crucibles with embedded heaters is described by Olsen, Smith, and Crittenden.

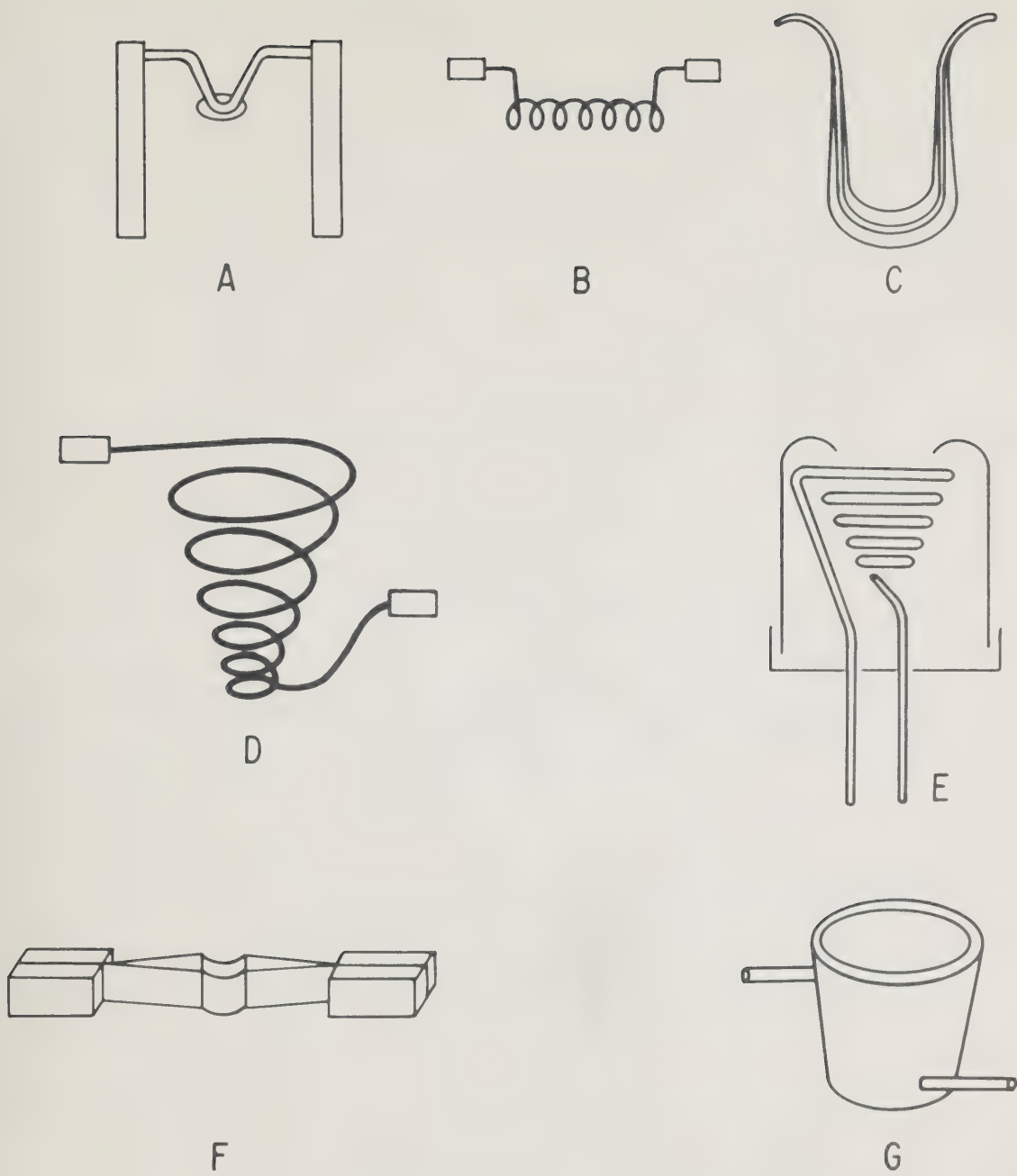


Fig. 7 Typical evaporation sources.

XIV. MANIPULATION OF VOLATILE COMPOUNDS

R. T. Sanderson (Vacuum Manipulation of Volatile Compounds, John Wiley and Sons, New York, 1948) has compiled a great deal of information concerning the application of vacuum techniques to the handling and purification of volatile compounds.

Low temperature distillation is the technique most often used to purify or transfer these materials in a vacuum system.

The methods of producing and measuring low temperatures, therefore, are very important.

A. METHODS OF PRODUCING LOW TEMPERATURES

Methods of producing low temperatures include the use of a material at its boiling point, at its sublimation point, at its freezing point, or the use of a heat transfer medium and an external source of power.

1. Boiling Point

Materials used at their boiling point include liquid nitrogen (bp = -196°C at 760 torr) and liquid oxygen (bp = -183°C at 760 torr). The temperature of liquid nitrogen can be reduced to about -210°C (i. e., the temperature of the triple point) by pumping on it.

2. Sublimation Point

Solid carbon dioxide (dry ice) sublimates (changes from a solid to a gas) at -78.5°C at 760 torr. Temperatures as low as -100°C can be achieved by pumping on the dry ice.

Dry ice is frequently powdered and added to a liquid (like acetone or Dowanol). These liquids are still fluid at -78.5°C and provide an effective heat transfer fluid.

3. Freezing Point--Slush Baths

Slush baths, or solid-liquid mixtures at their freezing points, are convenient means for achieving a variety of constant temperatures. They are

prepared by rapidly stirring the liquid compound as it is cooled to its freezing point. Frequently liquid nitrogen is poured into the liquid to cool it.

Fixed standard temperatures can be obtained with the following compounds (if they are of high purity):

<u>Compound</u>	<u>Melting Point (°C)</u>
Water	0.0
Carbon tetrachloride	-22.9
Chlorobenzene	-45.2
Chloroform	-63.5
Ethyl acetate	-83.6
Carbon disulfide	-111.6
Methylcyclohexane	-126.3

Other materials which have been suggested for constant low temperature slush baths include:

<u>Compound</u>	<u>Melting Point (°C)</u>
Eucalyptol	- 2
Acetonyl acetone	- 6
Methyl salicylate	- 9
Diethylene glycol	-11
t-Amyl alcohol	-12
Benzaldehyde	-14
Diethyl carbonate	-15
Octyl alcohol	-18
Butyl benzoate	-20
Carbon tetrachloride	-23
Diethyl sulfate	-25
Diamylnaphthalene	-30
Dipropyl ketone	-33
Ethylene dichloride	-36

Diethyl ketone	-42
Tetrachloroethylene	-44
Chlorobenzene	-46
Ethyl malonate	-50
Diacetone alcohol	-55
Amylnaphthalene	-60
Chloroform	-64

4. Heat Transfer Liquids

Nonflammable liquids that have been used for heat transfer fluids for cooling baths include the following liquids and mixtures of liquids:

<u>Weight %</u>	<u>Material</u>	<u>Minimum Temp (°C)</u>
100	Carbon tetrachloride	- 23
100	Chloroform	- 63
49.4	Carbon tetrachloride	- 81
50.6	Chloroform	
100	Ethyl bromide	-119
19.7	Chloroform	-139
44.9	Ethyl bromide	
13.8	trans-1, 2, -Dichloroethylene	
21.6	Trichloroethylene	
14.5	Chloroform	-145
25.3	Dichloromethane	
33.4	Ethyl bromide	
10.4	trans-1, 2-Dichloroethylene	
16.4	Trichloroethylene	
18.1	Chloroform	-150
8.0	Ethyl chloride	
41.3	Ethyl bromide	
12.7	trans-1, 2-Dichloroethylene	
19.9	Trichloroethylene	

Pentane may be used down to -160°C and propane down to -196°C.

B. MEASURING LOW TEMPERATURES

1. Liquid Thermometers

Liquid (in glass) thermometers are convenient. Toluene is usable down to -95.1°C , n-pentane to -131.5°C , and iso-pentane to -159.7°C .

2. Vapor Pressure Thermometers

Vapor pressure thermometers are also very useful. In these devices a small amount of a pure material is enclosed in a small volume, which is connected to a manometer. The temperature is obtained from the measured pressure and the vapor pressure-temperature data for the pure compound. The following compounds have been used for vapor pressure thermometer fluids:

<u>Compound</u>	<u>Temperature Range ($^{\circ}\text{C}$)</u>
Carbon disulfide	25 to -10
Sulfur dioxide	-10 to -40
Ammonia	-30 to -77
Carbon dioxide	-75 to -100
Hydrogen chloride	-85 to -111
Ethylene	-100 to -150
Methane	-150 to -185
Oxygen	-180 to -200

3. Resistance Thermometers and Thermocouples

Platinum resistance thermometers and thermocouples are frequently used. Copper-constantan thermocouples are used over the range -200° to 350°C .

XV. MISCELLANEOUS INDUSTRIAL APPLICATIONS

A. EVAPORATED FILMS

Evaporated metal films are used for optical coating, resistors, cryotron circuits, decorative purposes, etc.

B. VACUUM DRYING

Vacuum drying is a convenient low-temperature method for removing water and other volatiles from a variety of materials. These include coal, foundry sand, cement, paper, food stuffs, tobacco, textile fibers, sugars, chemicals and pharmaceutical products.

Vacuum drying has the advantage of taking place in absence of air and at a low temperature.

Freeze drying is done at temperatures below zero. This method has been especially useful in the drying of blood plasma, surgical grafts and tissues, antibiotics, hormones, etc.

C. VACUUM IMPREGNATION

Vacuum impregnation of casting, high voltage paper capacitors, high voltage electrical cables, wood, etc. is widely practiced.

D. DISTILLATION

Distillation is often carried out under reduced pressure.

E. METALLURGY

Vacuum is often used in metallurgy to produce metals of high purity with low gas constant. It has also aided in the formulation of new alloys. The use of vacuum in metal joining operations has already been discussed in Section VIII.

XVI. SURFACE CHEMISTRY AND PHYSICS

A. GENERATION OF CLEAN SURFACES

Any experiment designed to study the physical or chemical properties of a surface whose composition is to be representative of the bulk material requires the preparation of a surface free of contamination and the maintenance of cleanliness for a time that is sufficient to perform the experiment. If the time is only a few seconds, then the surface may be generated in a vacuum of about 10^{-6} torr. If, however, the time required is of the order of several minutes or hours, then the surface must be prepared and maintained in a vacuum of the order of 10^{-9} torr or less.

By an atomically clean surface, we adopt the recent definition that states that an atomically clean surface is one free of all but a few per cent of a single monolayer of foreign atoms, either adsorbed on or substitutionally replacing surface atoms of the parent lattice.

Six methods that have been used separately or in combination to generate clean surfaces include evaporating a material onto a substrate, high-temperature heating, chemical reaction, cleaving or crushing a crystal, eroding the substrate by ion bombardment (sputtering), and field desorbing part of the substrate. We shall consider the procedures, advantages, and disadvantages of these methods and shall give several specific examples of each.

B. SURFACE SENSITIVE PHENOMENA

The following surface sensitive phenomena have been used to study the properties of clean surfaces: catalysis, flash filament, work function, photo-electric emission, field electron and ion emission, low energy electron diffraction, secondary electron emission, and Auger electron emission.

We shall discuss the principles of these methods and illustrate each with specific examples.

C. REFERENCES

- R.W. Roberts
"Generation of Clean Surfaces in High Vacuum"
Brit. J. Appl. Phys., 14, 537 (1963).
R.W. Roberts and T.A. Vanderslice, op. cit.

XVII. MANUFACTURERS OF VACUUM EQUIPMENT
AND SPECIAL MATERIALS
(from Pirani and Yarwood, op. cit.)

In this list the names of those manufacturers who supply a range of vacuum equipment are marked with an asterisk. In the case of other firms which produce certain specialized apparatus valuable in vacuum technology, the products concerned are noted in brackets. Only the name and address of the principal manufacturing concern is given.

*Associated Electrical Industries (Manchester) Ltd., Instrumentation Division (formerly Metropolitan-Vickers Electrical Co., Ltd.), Trafford Park, Manchester 17, England.

Atlas-Werke A.G., Department Mat., Bremen, Germany (membrane manometers, vacuum valves, cold-traps, mass spectrometers for leak detection).

Beach-Russ Co., 420 Lexington Avenue, New York 17, U.S.A. (mechanical rotary pumps).

Beckman Instruments Inc., 2500 Fullerton Road, Fullerton 1, California, U.S.A. (mass spectrometers).

A. le Boeuf et fils, 194 Rue des Gros-Grès, Colombes, France (ionization gauges).

Celtiques, 107 Av. du Président, Montreuil (Seine), France (vacuum pumps, valves).

*Central Scientific Co., 1700 Irving Park Road, Chicago 13, Illinois, U.S.A.

Chapman Valve Manufacturing Co., Essex Street, Indian Orchard, Massachusetts, U.S.A. (vacuum isolation valves)

Compagnie Générale de T.S.F., 55 Rue Greffulhe, Levallois-Perret (Seine), France (ionization gauges).

*Compagnie Générale de Radiologie, Department Vide, 48 to 50 Boulevard Gallieni, Issy-les-Moulineaux, Seine, France.

*Consolidated Electrodynamics Corp., Rochester Division, Rochester 3, New York, U.S.A.

Degussa Wolfgang Industrieofenbau, Wolfgang bei Hanau, Main, Germany (vacuum furnaces).

*Deutsche Vakuumanapparate, Dreyer und Holland-Merten G.m.b.H., Sangerhausen, East Germany.

Dupree Swift and Co., Ltd., 23-25 Broadwall, Stamford Street, London, S.E. 1, England (Dewar flasks).

*Edwards HighVacuum Ltd., Manor Royal, Crawley, Sussex, England

Electrothermal Engineering Ltd., 270 Neville Road, London, E. 7, England (heating mantles and tapes).

- *Etablissements Beaudouin, 1 et 3, Rue Rataud, Paris, 5e, France.
- Etablissements P. Piel, 48 Rue du Faubourg, Saint Denis, Paris 10, France
(mechanical rotary pumps)
- Ferranti Ltd., Hollinwood, Lancs., England ('Tesvac' coil, ion pumps).
- General Electric Co., Vacuum Products Operation, Schenectady, N.Y., U.S.A.
- *Genevac Ltd., [a subsidiary of General Engineering Co. (Radcliffe), Ltd.],
Pioneer Mill, Radcliffe, Lancs, England.
- *Geraetebau-Anstalt Balzers, Liechtenstein.
- Granville-Phillips Co., P.O. Box 1290, Boulder, Colorado, U.S.A. (ultra-
high vacuum valves).
- Hastings-Raydist Inc., Hampton 10, Virginia, U.S.A. (vacuum gauges).
- *W.C. Heraeus G.m.b.H., Abteilung Hochvakuum, Hanau, Germany.
- Hilliard Corp., 211 W. Fourth St., Elmira, New York, U.S.A. (oil purifiers
for rotary pumps).
- Jenaer Glaswerk Schott and Gen., 10 Hattenbergstrasse, Mainz, W. Germany
(glass oil diffusion and ejector pumps; glass accessories).
- E. Kammerer, 40 Bergstrasse, Bergisch Gladbach, Germany (mercury
manometers and McLeod gauges of the Kammerer type).
- Kemet Co., (a division of Union Carbide and Chemical Corp.), Madison Avenue
and W. 117th Street, Cleveland Ohio, U.S.A. (getters)
- Kestner Evaporator and Engineering Co., Ltd., 5 Grosvenor Gardens, London
S.W. 1, England (drying towers).
- Kinney Manufacturing Division, The New York Air Brake Co., 3522F Washington
Street, Boston 30, Massachusetts, U.S.A. (mechanical rotary pumps).
- Klein, Schanzlin and Becker A.G., Frankenthal, Germany (piston pumps, water-
ring pumps).
- *Laboratoire des Basses Pressions, 87 Rue A.G. Bélin, Argenteuil, France.
- *Leybold Elliott Ltd., Elstree Way, Boreham Wood, Herts, England.
- *E. Leybold's Nachfolger, also Leybold Hochvakuum Anlagen, 504 Bonnerstrasse,
Cologne-Bayental, Germany.
- Maschinenfabrik Burkhardt A.G., Basle, Switzerland (mechanical rotary pumps,
water-ring pumps, vacuum driers).
- *Micafil S.A., Zurich, Switzerland.
- Mirrlees Watson Co., Ltd., Scotland Street, Glasgow, C. 5, Scotland (steam
ejector pumps).

Mullard Ltd., Materials Division, Mullard House, Torrington Place, London, W.C. 1, England (ionization gauges, small glass getter-ion pumps, ultra-high vacuum valves).

Murex Ltd., Powder Metallurgy Division, Rainham, Essex (vacuum resistance furnaces).

*National Research Corp., Vacuum Engineering Division, 70 Memorial Drive, Cambridge 42, Massachusetts, U.S.A., also NRC Equipment Corp., 160 Charlemont Street, Newton Highlands 61, Massachusetts, U.S.A.

*N. G. N. Electrical Ltd., Avenue Parade, Accrington, England.

*Officine Galileo, Florence, Italy.

*A. Pfeiffer G.m.b.H., 31 Bergstrasse, Wetzlar, Lahn, Germany.

C. Pfister S.A., Secfroid, Lausanne, Switzerland (vacuum drying).

Philips Gloeilampenfabrieken, Eindhoven, Holland (vacuum gauge tubes; gas liquefying machines).

*Pulsometer Engineering Co., Ltd., Nine Elms Iron Works, Reading, Berks., England.

W.G. Pye and Co., Ltd., Granta Works, Cambridge, England (Pirani-ionization gauge combination).

Radio Corporation of America, Electron Tube Division, 415 S. Fifth St., Harrison, New York, U.S.A. (vacuum gauge tubes).

Saunders Valve Co., Ltd., Diaphragm Valve Division, Cwmbran, Monmouthshire, Wales (Saunders valves).

Siemens Edison Swan Ltd., 155 Charing Cross Road, London, W.C. 2, England (vacuum gauge tubes; glass-to-metal seals).

Società Apparecchi Elettrici e Scientifici, 215 Via Gallarate, Milan, Italy (getters).

G. Springham and Co., Harlow New Town, Essex, England (glass stopcocks).

*F. J. Stokes Corp., 5500 Tabor Road, Philadelphia 20, U.S.A.

Sunvic Controls Ltd., No. 1 Factory Eastern Industrial Estate, Harlow, Essex, England (hot wire vacuum switches).

Superior Air Products Co., 132 Malvern Street, Newark 5, New Jersey, U.S.A. (Dewar flasks)

Townson and Mercer Ltd., Beddington Lane, Croydon, Surrey, England (vacuum ovens).

Ultek Corp., 920 Commercial Street, Palo Alto, California, U.S.A. (ion pumps).

Vacuum Applied, 290 Rue de Chareton, Paris, 12e, France.

*Vacuum Industrial Applications Ltd., Netherton Road, Wishaw, Lanarkshire, Scotland.

Vacuum Metallurgical Developments Ltd., Shelford, Cambridge, England (vacuum furnaces, vacuum valves).

*Vacuum Research (Cambridge) Ltd., Quayside, Bridge Street, Cambridge, England (vacuum deposition apparatus, vacuum furnaces).

Vacuum Research Co., 420 Market Street, San Francisco 11, California, U.S.A. (vacuum valves).

Varian Associates, Palo Alto 26, California, U.S.A. (VacIon pumps).

*W.M. Welch Scientific Co., 1515 Sedgwick Street, Dept. VA, Chicago 10, Illinois, U.S.A.

Wild-Barfield Electric Furnaces Ltd., Elecfurn Works, Otterspool Way, Watford By-pass, Watford, Herts., England (vacuum furnaces).

The list is concerned with manufacturers of specialized material used in vacuum technology.

American Lava Corp., 210 Kruesi Building, Chattanooga 5, Tennessee, U.S.A.

G. Angus and Co., Ltd., Oil Seal Division, Coast Road, Wallsend, Northumberland (Gaco seals).

Associated Electrical Industries (Rugby) Ltd., (formerly British Thomson Houston Co., Ltd.), Rugby, England.

Baker and Co., 113 Astor Street, Newark, New Jersey, U.S.A.

Bell's Asbestos and Engineering Co., Ltd., Bestabell House, 6-8 Upper Thames Street, London, E.C. 4, England.

Bergen Wire Rope Co., 1234 Gregg Street, Lodi, New Jersey, U.S.A.

J. G. Biddle Co., 1316 Arch Street, Philadelphia 7, U.S.A.

British Aluminium Co., Ltd., Norfolk House, St. James Sq., London, S.W. 1, England.

British Drug Houses Ltd., Poole, Dorset, England.

British Oxygen Gases Ltd., East Lane, Wembley, Middx., England.

W. Canning and Co., Ltd., Great Hampton Street, Birmingham 18, England.

Carrs Paints Ltd., Artillery Street, Birmingham 9, England.

Catalin Ltd., 54 Farm Hill Road, Waltham Abbey, Essex, England.

Cathodeon Ltd., Church Street, Cambridge, England.

Chance Bros. Ltd., Lighthouse Works, Smethwick 40, Birmingham, England.

Ciba (A.R.L.) Ltd., Duxford, Cambridge, England.

Corning Glass Works, 1946 Crystal Street, Corning, New York, U.S.A.

Cray Valley Products, Cray Valley, St. Mary Cray, Kent, England.

Creators Ltd., Silmay Works, Kings Road, New Haw, Weybridge, Surrey, England.

Croid Ltd., Imperial House, 15-19 Kingsway, London, W.C. 2, England.

Cynamid Products Ltd., Brettenham House, Lancaster Place, London, W.C. 2, England.

Dalton Ballard and Co., Ltd., Fleet Place, Upper Park Road, London, N.W. 3, England (suppliers of 'Sindanyo').

Dow Corning Corp., Midland, Michigan, U.S.A. (silicone products).

Dunlop Rubber Co., St. James's House, St. James's Street, London, S.W. 1, England.

Enthoven Solders Ltd., Upper Ordnance Wharf, Rotherhithe Street, London, S.E. 16, England.

Ferguson Edwards, The Maltings, Abbey Road, Barking, Essex, England.

Flexibox Ltd., Mechanical Seals, 76 Jermyn Street, London, S.W. 1, England.

Fry's Metal Foundries Ltd., Tandem Works, Merton Abbey, London, S.W. 19, England.

Garlock Packing Co., Palmyra, New York, U.S.A.

Geigy Ltd., 46 Old Bond Street, London, W.C. 1, England.

General Electric Co., Ltd., Magnet House, Kingsway, London, W.C. 2, England.

Griffiths Bros., Marks Road, London, S.E. 16, England.

Hardman and Holden, Manox House, Canal Street, Manchester 10, England.

Hulburd Patents Ltd., 26 Park Road North, London, W. 3, England.

Imperial Chemical Industries Ltd., Paints Division, Wexham Road, Slough, Bucks., England.

Imperial Chemical Industries Ltd., Plastics Division, Black Fan Road, Welwyn Garden City, Herts., England.

Jenaer Glaswerke, Schott und Gen., 10, Hattenbergstrasse, Mainz, West Germany.

Johnson and Matthey Ltd., 78-83 Hatton Garden, London, E.C. 1, England.

Knapsack-Griesheim A.G., Knapsack near Cologne, Germany.

Kulite Tungsten Co., Ridgefield, New Jersey, U.S.A.

Libbey-Owens-Ford Glass Co., 608 Madison Avenue, Toledo 3, Ohio, U.S.A.

Linde's Eismaschinen A.G., 76 Nymphenburgerstrasse, Munich 2, Germany.

Marinite Ltd., 25 and 27 North Row, London, W. 1, England.
 Megatron Ltd., 105A, Fonthill Road, London, N. 4, England.
 Metallwerk Plansee, Reutte, Tirol, Austria.
 Midland Silicones Ltd., 19 Upper Brook Street, London, W. 1, England.
 Mond Nickel Co., Ltd., Thames House, Millbank, London, S.W. 1, England.
 Morgan Crucible Co., Ltd., Battersea Works, Battersea Church Road, London, S.W. 11, England.
 Murex Ltd., Rainham, Essex, England.
 Nu-Finishes Ltd., 466 London Road, Croydon, Surrey, England.
 Perdeck Solder Products Ltd., Abbey Mills, Waltham Abbey, Essex, England.
 Phenogaze Ltd., 466 London Road, Croydon, Surrey, England.
 Plowden and Thompson Ltd., Stourbridge, Worcester, England.
 Powell Duffryn Carbon Products Ltd., Springfield Road, Hayes, Middx., England.
 Precision Rubbers Ltd., Bagsworth, Leics., England.
 Redifon Ltd., Broomhill Road, London, S.W. 18, England.
 The Sheffield Smelting Co., Ltd., Royds Mill Street, Sheffield 4, Yorks., England.
 Shell Chemical Co., Ltd., Norman House, 105 9. Strand, London, W.C. 2, England.
 Steatite and Porcelain Products Ltd., Stourport-on-Severn, Worcestershire, England.
 Sylvania Electric Products Inc., 1740 Broadway, New York 19, U.S.A.
 Thermal Syndicate Ltd., 9 Berkeley Street, London, W. 1, England.
 Thornley and Knight Ltd., Green Road, Bordesley, Birmingham 9, England.
 Telefunken G.m.b.H., 100 Söflingerstrasse, Ulm Donau, W. Germany.
 Tungsten Manufacturing Co., 68 Victoria Street, London, S.W. 1, England.
 Vactite Ltd., 75 St. Simon St., Salford 3, Lancs., England.
 G. and I. Weir Ltd., Cathcart, Glasgow, S. 4, Scotland.
 Westinghouse Electric Corp., East Pittsburgh, Pennsylvania, U.S.A.
 Winslow Engineering Co., Newark, New Jersey, U.S.A.

APPENDIX A

I. MOLECULAR FLOW CONDUCTANCES--SUMMARY OF FORMULAS

These equations are for the conductance of air at 20°C. To apply to a gas of molecular weight M at temperature T (°K), multiply the equation by $\sqrt{\frac{T \times 29}{M \times 293}}$. All dimensions are given in cm.

1. Aperture

$$C = 11.6 \times A \text{ liter sec}^{-1} \quad (A1)$$

A = area aperture

2. Aperture in End of Pipe

$$C = C_A \frac{A_0}{A_0 - A} \text{ liter sec}^{-1} \quad (A2)$$

C_A = conductance of aperture; see Eq. (A1)

A_0 = area of pipe

A = area of aperture

3. Long Circular Pipe

$$C = 12.1 \frac{d^3}{l} \text{ liter sec}^{-1} \quad (A3)$$

d = diameter

l = length

4. Short Circular Pipe

$$C = 12.1 \frac{d^3}{l} \alpha \text{ liter sec}^{-1} \quad (A4)$$

$\alpha = f\left(\frac{l}{d}\right)$; see page 25

5. Circular Annulus (region between two coaxial circular pipes)

$$C = 12.1 \frac{(d_1 - d_2)^2 (d_1 + d_2)}{l} \text{ K liter sec}^{-1} \quad (A5)$$

d_1 = diameter outside pipe

d_2 = diameter inside pipe

$K = f(d_2/d_1)$,

d_2/d_1	0	0.259	0.500	0.707	0.866	0.966
K	1	1.072	1.154	1.254	1.430	1.675

6. Long Rectangular Pipe

$$C = 30.9 \frac{a^2 b^2}{(a+b)\ell} K' \text{ liter sec}^{-1} \quad (A6)$$

a = dimension of long side of rectangle

b = dimension of short side of rectangle

$K' = f(b/a)$

b/a	1	0.667	0.500	0.333	0.200	0.125	0.100
K'	1.108	1.126	1.151	1.198	1.297	1.400	1.444

7. Long Equilateral Triangular Pipe

$$C = 4.79 \frac{a^3}{\ell} \text{ liter sec}^{-1} \quad (A7)$$

a = dimension of side of triangle

8. Long Elliptical Pipe

$$C = 96.5 \frac{ab^2}{\ell} \text{ liter sec}^{-1} \quad (A8)$$

a = semimajor axis of ellipse

b = semiminor axis of ellipse

9. Thin Slit-Like Tube

$$C = 30.9 \frac{ab^2}{\ell} K'' \text{ liter sec}^{-1} \quad (A9-1)$$

where $a \gg b$

a = long dimension of slit

b = short dimension of slit

$K'' = f(\ell/b)$

ℓ/b	0.1	0.2	0.4	0.8	1	2	3	4	5	10
K''	0.036	0.068	0.13	0.22	0.26	0.40	0.52	0.60	0.67	0.94
ℓ/b	> 10									

$$K'' = \ln \frac{3}{8} \left(\frac{\ell}{b} \right)$$

Thus for a long slit-like tube

$$C = 27 \frac{ab^2}{\ell} \log \left(\frac{\ell}{b} \right) \quad (\text{A9.2})$$

10. . Annular Aperture (thin circular disk in circular pipe)

$$C = 11.6 AK \text{ liter sec}^{-1} \quad (\text{A10})$$

A = area annular aperture

$$= \frac{\pi}{4} (d_1^2 - d_2^2)$$

d_1 = diameter pipe

d_2 = diameter disk

K = f (d_1/d_2) same as K in circular annulus--Eq. (A-5)

11. Bend or Elbow (circular cross section)

C $\cong$ conductance of a short circular pipe of the same diameter and of length equal to the axial length of the bend (A11)

II. CALCULATION OF CONDUCTANCE--EXAMPLE

Calculate the conductance, C, of the following cylindrical cold trap that isolates a vacuum system from a diffusion pump.

Dimensions

$$d_1 = 10 \text{ cm}$$

$$d_2 = 8 \text{ cm}$$

$$d_3 = 5 \text{ cm}$$

$$\ell_1 = 3 \text{ cm}$$

$$\ell_2 = 15 \text{ cm}$$

$$\ell_3 = 3 \text{ cm}$$

To calculate the total conductance, we must first calculate the following individual conductances:

C_1 = cond. of an aperture of diam 10 cm

C_2 = cond. of pipe 3 cm long

C_3 = cond. of annular aperture

C_4 = cond. of circular annulus

C_5 = cond. of pipe 3 cm long

C_6 = cond. of aperture in end of pipe.

$$\begin{aligned} C_1 &= 11.6 \text{ A} & [\text{use Eq. (A1)}] \\ &= 11.6 \times \pi (5)^2 \\ &= 910 \text{ liter sec}^{-1} \end{aligned}$$

$$\begin{aligned} C_2 &= 12.1 \frac{d^3}{l} & [\text{use Eq. (A3)}] \\ &= \frac{12.1 (10)^3}{3} \\ &= 4030 \text{ liter sec}^{-1} \end{aligned}$$

$$\begin{aligned} C_3 &= 11.6 \text{ AK} & [\text{use Eq. (A10)}] \\ &= (11.6) (0.25) \pi [(10)^2 - (8)^2] (1.37) \\ &= 449 \text{ liter sec}^{-1} \end{aligned}$$

$$\begin{aligned} C_4 &= 12.1 \frac{(d_1 - d_2)^2 (d_1 + d_2)}{l} \text{ K} & [\text{use Eq. (A5)}] \\ &= 12.1 \frac{(10 - 8)^2 (10 + 8)}{15} (1.37) \\ &= 79.5 \text{ liter sec}^{-1} \end{aligned}$$

$$\begin{aligned} C_5 &= C_2 \\ &= 4030 \text{ liter sec}^{-1} \end{aligned}$$

$$\begin{aligned} C_6 &= 11.6 \text{ A} \frac{A_0}{A_0 - A} & [\text{use Eq. (A2)}] \\ &= 11.6 \pi (2.5)^2 \frac{\pi (5)^2}{\pi [(5)^2 - (2.5)^2]} \\ &= 300 \text{ liter sec}^{-1} \end{aligned}$$

$$\begin{aligned}
\frac{1}{C} &= \sum_i \frac{1}{C_i} \\
&= \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \frac{1}{C_4} + \frac{1}{C_5} + \frac{1}{C_6} \\
&= \frac{1}{910} + \frac{1}{4030} + \frac{1}{449} + \frac{1}{79.5} + \frac{1}{4030} + \frac{1}{300} \\
&= (1.1 + 0.248 + 2.13 + 12.58 + 0.248 + 3.33) \times 10^{-3} \\
&= 19.636 \times 10^{-3}
\end{aligned}$$

Thus $C = 51 \text{ liter sec}^{-1}$

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APPENDIX B

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GENERAL ELECTRIC

Research Laboratory

SCHENECTADY, NEW YORK

TECHNICAL INFORMATION SERIES

Title Page

AUTHOR Roberts, R. W.		SUBJECT CLASSIFICATION high vacuum technology		NO. (Revised) 64-RL-3394 C	
				DATE September 1964	
TITLE An Outline of Vacuum Technology					
ABSTRACT This report comprises a portion of the lecture material developed for a course in high vacuum technology, which was presented at the Research Laboratory (February to May 1963 and September to December 1963). The main divisions are: I. Introduction II. History of Vacuum Technology					
G.E. CLASS 1		REPRODUCIBLE COPY FILED AT Research Information Section The Knolls Schenectady, New York		NO. PAGES 125	
GOV. CLASS					
III. Primary Quantities, Units, and Constants IV. Empirical Relations and the Kinetic Theory of Gases V. The Transport of Gas in Vacuum Systems VI. Pumping VII. Gauges VIII. Vacuum Seals IX. Valves X. Materials of Construction XI. System Design XII. Leak Detection XIII. Deposition of Films XIV. Manipulation of Volatile Compounds XV. Miscellaneous Industrial Applications XVI. Surface Chemistry and Physics XVII. Manufacturers of Vacuum Equipment and Special Materials					

By cutting out this rectangle and folding on the center line, the above information can be fitted into a standard card file.

INFORMATION PREPARED FOR:

SECTION: Polymer and Interface Studies

DEPARTMENT: Chemistry Research

HOW IT ALL STARTED

CONFLAT® FLANGES

Mark the year 1962 as one of special significance to the scientific community. It was then that Varian introduced ConFlat Flanges. Before their appearance (and their leak-tight, bakeable seals), an incredible amount of time was spent keeping vacuum systems leak-free. The ConFlat Flange released engineers and scientists to get on with the work at hand. We can safely say that many technological advances have been achieved because of improved vacuum techniques made possible by ConFlat Flanges.

Are you wondering what is so great about ConFlat Flanges? Here are some of the features that have led to the worldwide sale of hundreds of thousands of them:

A temperature range from below -196°C to above $+500^{\circ}\text{C}$.

Identical flange seals — no male and female halves. And no special techniques required for sealing.

A proved immunity to leaks from gasket scratches and flange nicks. No polishing or refinishing of flanges between seals.

They seal with inexpensive, flat, copper gaskets.

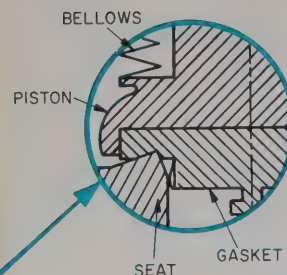
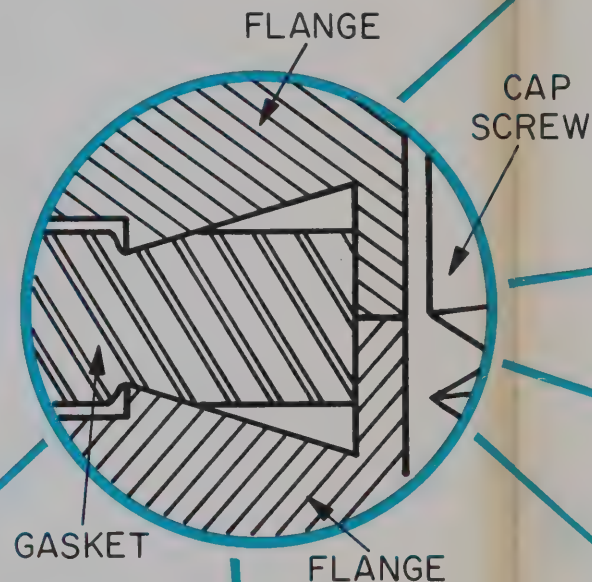
They come in standardized sizes.

COMPATIBILITY. Any ConFlat Flange mates with another of the same outside dimension.

The reliable sealing performance results from the design geometry (U. S. patent 3,208,758) which "captures" the gasket material. High interface pressures are developed that cause gasket material to fill surface imperfections and produce a near-perfect fit. At high temperatures, the capturing geometry maintains high interface pressures despite softening of the gaskets.

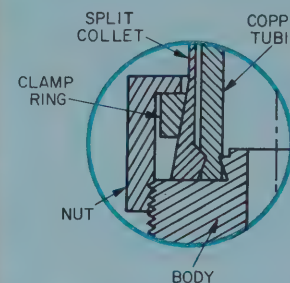
You'll find the capturing principle, combined with additional unique features, applied in the design of a wide variety of components. For some, bakeout temperature ratings are less than 500°C because of sealing force limitations. But leak-tight reliability is the same.

Let's look at the components that have proliferated.



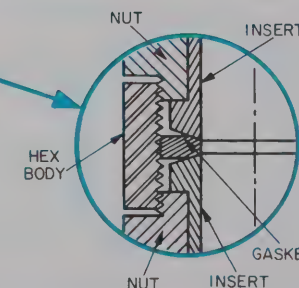
BAKEABLE VALVES

All-metal valves in right-angle, tee and straight-through configurations are bakeable to 450°C either open or closed. They also operate submerged in liquid nitrogen. The removable gasket is pressed into the piston and is captured between piston and seat to make the reliable seal. These valves come in several standard sizes.



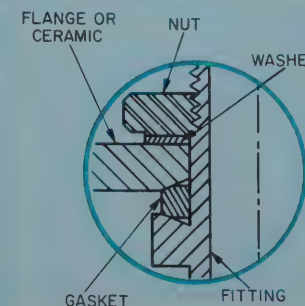
COMPRESSION PORTS

Connectors for copper exhaust tubing are needed particularly for pumping stations for metal and ceramic microwave tubes. The copper tubulation is forced against the body's sealing surface by the split collet to make the vacuum seal. While rated to 500°C , temperatures up to 750°C have been achieved with no leaks. Standard models accept tubing of $\frac{3}{8}$, $\frac{1}{2}$ and $\frac{3}{4}$ -inch outside diameter.



TUBE COUPLING

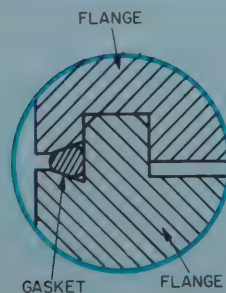
A compact, demountable coupling for $\frac{1}{2}$ -inch O.D. stainless steel tubing is bakeable to 450°C with leak-tight reliability. Inserts are welded to connecting tubing and wrench tightening makes the seal on a rectangular cross-section OFHC copper gasket.



LIQUID FEEDTHROUGH (Stainless Steel) and RF FEEDTHROUGH

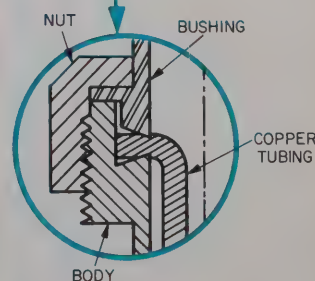
These demountable seals are made by compressing a rectangular OFHC copper gasket between the fitting and metal flange or ceramic disc. In the liquid feedthrough, the metal flange is used where the stainless-steel liquid transfer lines are attached by welding. Temperature range is -196°C to $+450^{\circ}\text{C}$.

In the 20 kW rf Feedthrough, connecting lines inside the vacuum are brazed to the fittings, and the two fittings are sealed against a high alumina ceramic disc. Bakeout rating is 300°C .



WHEELER™ FLANGES

These flanges are used for seals of large diameter — from 10 $\frac{3}{4}$ inches to 6 feet. They employ copper wire gaskets and are used for sealing stainless steel bell jars, pumps and fittings. Connections made with Wheeler Flanges are leak-tight from -196°C to $+450^{\circ}\text{C}$.



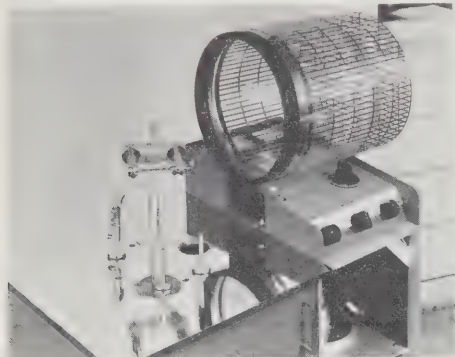
LIQUID FEEDTHROUGH (Copper Tubing)

This unique device seals on the flared end of $\frac{3}{8}$ -inch O.D. copper tubing. The external feedline can be of either copper or plastic tubing. Temperature range is -196°C to $+450^{\circ}\text{C}$.

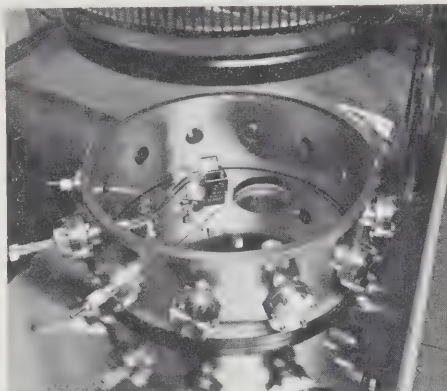
PRACTICAL DIFFUSION PUMP SYSTEMS

You may be giving thought to the variety of vacuum pumps that can work for you—mechanical, sorption, sputter-ion, diffusion, sublimation, cryogenic. Each does a particular pumping job best. Often it takes a mixture of

pump types to solve a vacuum problem. Although Varian has pioneered in the development of *new* pumping mechanisms, we're quick to recommend only the design concepts that are *most appropriate* for your specific need.

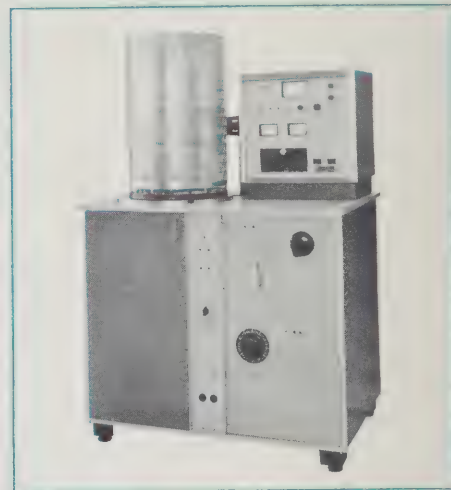


No vacuum experience is required to operate this automatic 2-inch diffusion pump system. It is well suited for production of semiconductors and preparation of electron microscope specimens. More than 300 of this model are now in use.



A manually-operated 4-inch system is shown fitted with a collar containing an e-Gun™ Evaporation Source.

For instance, you might find one of our diffusion pump systems most efficient. They come in both automatic and manual models—all ready to plug in and go. Your local Marketing Engineer can guide your selection.



This new, automatic 6-inch diffusion pump system is set up for resistance heated evaporation work.



New Aluminum VacSorb Pumps: Triple, Double, Standard.

VACSORB® PUMPS — STANDARD, DOUBLE, TRIPLE

Now you can design your roughing system around off-the-shelf sorption pumps in three sizes. At first glance they may call to mind the story of the three bears, as they did to the young daughter of one of our engineers, but they are *not* bears at all. VacSorb Pumps are easy to use. Convenient. Just right for clean rough pumping. No oil — or vibration — or noise.

These new VacSorb Pumps have an automatic gas relief valve that always stays in place — and an integral heater that provides bakeout just by your turn-

ing a switch. They are ALUMINUM (except for the ConFlat Flange and connecting tubing) for the best heat transfer you can find in *any* sorption pump, and to eliminate internal oxidation from baking. You'll hear our VacSorb pumps referred to as the hottest cryosorption pumps around!

Would you like information on sorption pumping? Our research men have helped define the art. We can send you a reprint of an article on the theory of operation, and a data sheet with specifications of these new models.

ANNOUNCEMENT

You will soon receive in the mail the program for our Fifth Annual Vacuum Technology Seminar. For the first time, we will hold our seminar sessions in the East, in New York City, on April 10, 11, 12. We are also planning a three-day Symposium-Workshop on LEED (low energy electron diffraction) April 12-14 in New York. You may want to start planning now to attend one or both.

Varian Vacuum Views will be mailed to you every two months. We aim to be of service. For information and assistance with your vacuum work, please contact your local Marketing Engineer or the Vacuum Division, Varian, 611 Hansen Way, Palo Alto, California, 94303, (415) 326-4000.



varian/vacuum division/611 hansen way/palo alto, california



OF TIME, HEAT AND OUTER SPACE

About five years ago, people interested in nuclear space propulsion at NASA Lewis Flight Center became concerned about existing creep test data on refractory metal alloys. The metal alloys were known to have strength at elevated temperatures and good corrosion resistance. But how would they behave at temperatures as high as 1370°C (2500°F), over periods of time like 30,000 hours—more than three years?

Space program plans called for the use of metal alloys in a cooling system containing hot liquid sodium-potassium mixtures (notoriously corrosive). Also, while under the stresses created by the pressurized liquid, the outside of the metal alloy would be exposed to the ultra-high vacuum of outer space. And flights would be of long duration.

Sound like difficult conditions? NASA recognized the scope of the problem and set about getting answers. One program, awarded to Westinghouse Astronuclear Laboratories, specified tantalum base alloy creep tests at temperatures as high as 1920°C (3490°F) in a vacuum environment below 1×10^{-8} Torr.

This called for a new type of vacuum furnace. Previous commercial testing furnaces used oil diffusion pumps and operated in the 3×10^{-6} Torr region. We proposed a design that would provide completely *oil-free* vacuum and be reliable at ultra-high vacuum pressures. It used sorption roughing pumps and a getter-ion pump. Since carbon, oxygen and nitrogen can cause significant changes in the mechanical properties of refractory metal alloys at elevated temperatures, the ultra-high vacuum environment seemed essential for long-term testing.

Our first vacuum creep furnace was installed at Westinghouse in February, 1964. Cautiously, engineers ran preliminary side-by-side comparison tests on samples of T-111 (Ta-8W-2Hf) in a diffusion pumped furnace and in the new unit. The difference in results was

dramatic. In just 175 hours there was substantial carbon and oxygen pickup in the sample in the diffusion-pumped system. In the clean, ultra-high vacuum furnace, pickup was negligible. The photomicrographs show this comparison of contamination.

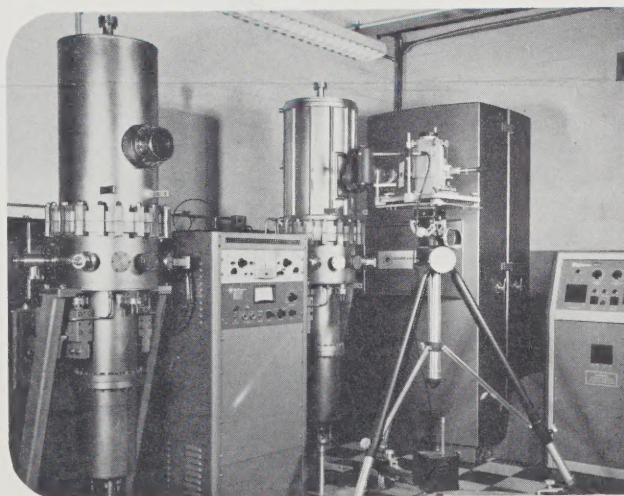
But would the contamination affect the performance of the metal alloy? Chemical analysis and mechanical testing confirmed that the creep test properties were so altered that much of the data collected previously at 3×10^{-6} Torr was undependable for the design of equipment to be used in outer space.

As a result, Westinghouse has five of our creep testing vacuum furnaces in operation around the clock. Their engineers have accumulated over 40,000 test hours at temperatures in the range of 1320°C (2400°F) to 1540°C (2800°F) at pressure below 1×10^{-8} Torr. In a parallel study, five other Varian ultra-high vacuum furnaces are in operation in the same room to age weld specimens for similar analysis.

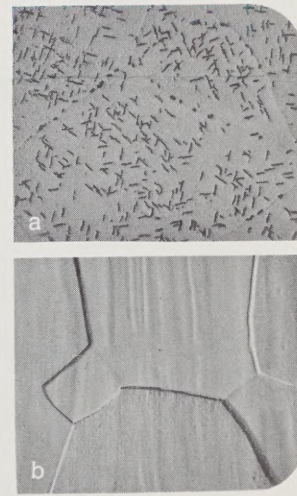
Other laboratories are also recognizing the importance of performing tests in high-temperature, ultra-high vacuum conditions. At the Donald W. Douglas Laboratories in Richland, Washington, for example, there is now a program under way to evaluate isotope fuels and cladding materials in furnaces of our design. Current tests have exceeded 2500 continuous hours at 2000°C (3630°F). The long-term goal is 10,000 continuous hours.

It appears that longer tests at lower pressures with high, stable temperatures are the research conditions that will expose fundamental properties in future materials studies. We presently make several types of furnaces that can provide these working conditions. If you would like further information, please ask us to send you:

- A reprint of an article from the October 1966 issue of THE REVIEW OF SCIENTIFIC INSTRUMENTS that describes the Westinghouse creep test furnace apparatus.
- Specifications of our clean, ultra-high vacuum furnaces.



Two Varian Ultra-high Vacuum Creep Testing Furnace Systems at the Westinghouse Astronuclear Laboratory



Microstructure of T-111 Creep Specimens Tested at 1325°C (2400°F) and 9190 psi stress (1500X)

a) Tested at 5×10^{-6} Torr
b) Tested at 1×10^{-8} Torr, oil-free system

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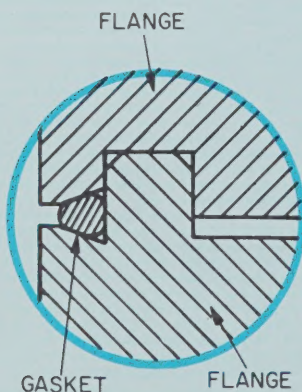
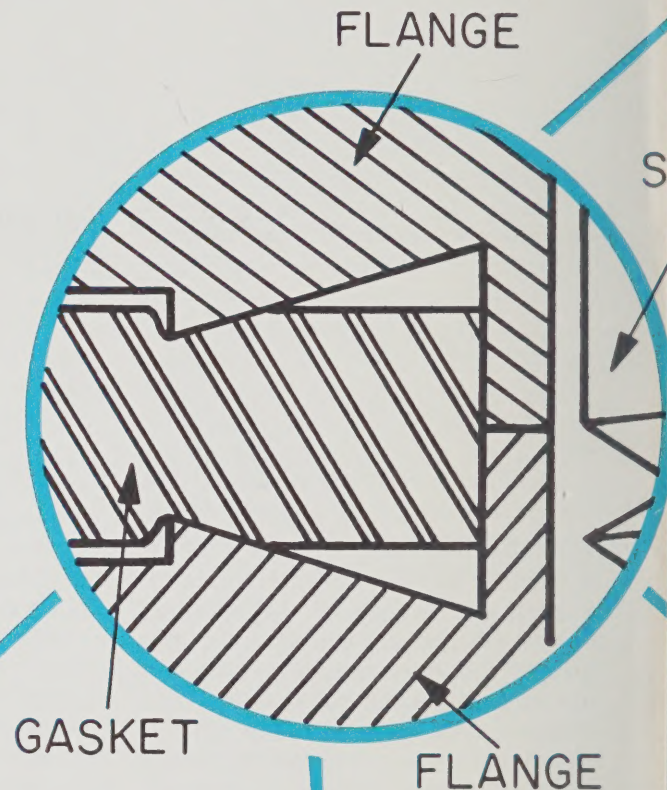
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The reliable sealing performance results from the design geometry (U. S. patent 3,208,758) which "captures" the gasket material. High interface pressures are developed that cause gasket material to fill surface imperfections and produce a near-perfect fit.

At high temperatures, the capturing geometry maintains high interface pressures despite softening of the gaskets.

You'll find the capturing principle, combined with additional unique features, applied in the design of a wide variety of components. For some, bakeout temperature ratings are less than 500°C because of sealing force limitations. But leak-tight reliability is the same.

Let's look at the components that have proliferated.



WHEELER™ FLANGES

These flanges are used for seals of large diameter — from $10\frac{3}{4}$ inches to 6 feet. They employ copper wire gaskets and are used for sealing stainless steel bell jars, pumps and fittings. Connections made with Wheeler Flanges are leak-tight from -196°C to $+450^{\circ}\text{C}$.

